

**University of Wisconsin Water Resources Institute  
Annual Technical Report  
FY 2015**

# Introduction

The University of Wisconsin Water Resources Institute (WRI) serves as the gateway to federal Water Resources Research Institute (WRRI) grants for all Wisconsin colleges and universities. While the WRI's federal base funding from the U.S. Geological Survey totals less than \$100,000 per year, every federal dollar is matched with at least two nonfederal dollars. All WRRI grants are awarded on a competitive, peer-reviewed basis. WRI funds are leveraged with additional funding from the UW System Groundwater Research Program, part of Wisconsin's Groundwater Research and Monitoring Program. Faculty members and research staff who have achieved PI status from any UW System campus are eligible to apply for this funding. Guided by the Wisconsin Groundwater Coordinating Council (<http://dnr.wi.gov/topic/groundwater/gcc/>), this program is the mechanism whereby the UW System and the state departments of Natural Resources, Safety & Professional Services, and Agriculture, Trade & Consumer Protection pool limited state and federal resources to support a coordinated, comprehensive and multidisciplinary response to the state's critical water resource issues. Together, these programs have helped establish the University of Wisconsin as a national leader in groundwater research. The Wisconsin WRI funds an average of 15 short-term research projects of either a fundamental or applied nature that typically involve dozens of faculty, staff and students at a half-dozen campuses around the state each year. By supporting short-term projects, the institute is able to quickly respond to issues as they emerge. WRI annually provides about 30 graduate and undergraduate students in the UW System with opportunities for training and financial support while they work toward their degrees.

WRI research and other water-related information is readily accessible via a website ([www.wri.wisc.edu](http://www.wri.wisc.edu)) and the Water Resources Library (WRL), a nationally unique collection of documents covering every major water resource topic. The library's catalog is available online and searchable via the Internet, making the WRL a national and global resource. The WRL became the first academic library in the state to make its collection available online to the public when it launched the "Wisconsin Water Library" ([www.aqua.wisc.edu/waterlibrary](http://www.aqua.wisc.edu/waterlibrary)) in 2003. The portal permits Wisconsin residents to check out WRL books and other documents free of charge via their local libraries.

WRI also helps organize and cosponsor state and regional conferences on water issues. The WRI is housed in the UW-Madison Aquatic Sciences Center, which also houses the UW Sea Grant Institute, part of another federal-state partnership of 33 university programs that promote research, education, and outreach on Great Lakes and ocean resources. This unique administrative union of Wisconsin's federal Water Resources Research Institute and Sea Grant programs enables the Aquatic Sciences Center to address the full range of water-related issues in Wisconsin, from surface water to groundwater, from the Mississippi River to the shores of Lakes Michigan and Superior.

## Research Program Introduction

As established by Wisconsin's Groundwater Law of 1984, the state provides \$270,000 annually to the UW System to support groundwater research and monitoring. In 1989, WRI became the UW System's lead institution for coordinating the proposal solicitation and review processes for prioritizing UWS groundwater project funding. WRI's priorities for groundwater research are established annually by the Wisconsin Groundwater Research Advisory Council (GRAC) made up of representatives from academia, federal and state agencies, and the private sector. The GRAC convenes annually to set priorities and to review and make recommendations to WRI on the selection of UW System-funded groundwater projects.

Also established in 1984, is the Wisconsin Groundwater Coordinating Council (GCC) (<http://dnr.wi.gov/topic/groundwater/gcc/>) which is made up of representatives of state agencies with groundwater protection responsibilities and state funding allocations, including the UW System and departments of Natural Resources, Safety & Professional Services, and Agriculture, Trade, & Consumer Protection. The GCC provides consistency and coordination among multiple state programs in funding groundwater monitoring and research to meet various program needs. To better target groundwater research funding, these state programs agreed to establish an annual Joint Solicitation for Wisconsin Groundwater Research and Monitoring. This solicitation is coordinated jointly to facilitate proposal writing, streamline the review process, curtail duplication, improve coordination among agencies and researchers, and enhance communication among the agencies and among principal investigators. WRI plays a lead role in coordinating the solicitation, a rigorous review process, project reporting and making all technical reports available through our institute's library and website. Collectively, this annual joint solicitation has funded 454 groundwater research and monitoring projects since its inception and has helped establish Wisconsin as an international leader in groundwater research. In FY15, 13 groundwater projects totaling over \$537k were funded through the Wisconsin Groundwater Research and Monitoring Program.

Although these projects are not funded with our 104(B) allocation, WRI is the administrator of the following UW System state-funded research projects during the federal FY15. Below, we include these and other non-UW System state-funded projects that were submitted, vetted, and selected through the Joint Solicitation for the Wisconsin Groundwater Research and Monitoring Program:

State-funded projects through the Wisconsin Groundwater Research and Monitoring Program during state FY 2016 (July 1, 2015-June 30, 2016), including title, investigators, affiliation, contract period, funding agency, and amount.

The Wonewoc and Tunnel City: A Potential Natural Source of Groundwater Contamination in Western & Central Wisconsin. Jay Zambito, Michael Parsen, Patrick McLaughlin, UW-Extension. 7/1/15-6/30/16. UW System. \$27,195.

Long-term Alterations in Groundwater Chemistry Induced by Municipal Well Pumping. Jean Bahr, Madeline Gotkowitz, UW-Madison and UW-Extension. 7/1/15-6/30/17. UW System. \$11,711.

Phosphorus & Arsenic Sensors for Real Time Environmental Monitoring. Daniel Noguera, Marc Anderson, UW-Madison. 7/1/15-6/30/17. UW System. \$47,541.

Engaging Stakeholders to Improve the Use of Groundwater Flow Models for Decision Making. Kenneth Genskow, Kenneth Bradbury. UW-Madison and UW-Extension. 7/1/15-6/30/16. UW System. \$ 41,966.

Predicting the locations of nitrate removal hotspots at the groundwater-surface water interface in Wisconsin streams. Robert Stelzer, UW-Oshkosh. 7/1/15-6/30/17. UW System. \$18,205.

## Research Program Introduction

Assessment of Environmental Impacts of Geothermal Source Heat Exchange. Christopher Choi, David Hart and James Tinjum, Wisconsin Geological and Natural History Survey. 7/1/2014 -6/30/16. UW System. \$40,649.

Hydrologic Impacts of the Loss of Wisconsin's Winter on Surface Water-Groundwater Interactions. Steven Loheide, UW-Madison. 7/1/2014 -6/30/16. UW System. \$37,414.

Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems. Matthew Ginder Vogel and Christina Remucal, UW-Madison. 7/1/2014 -6/30/16. UW System. \$13,811.

An updated springs inventory for the State of Wisconsin. Kenneth Bradbury and Susan Swanson, UW-Extension and Beloit College. 7/1/2014 -6/30/16. Department of Natural Resources. \$97,455.

Meeting the Source Assessment Requirement under the RTCR: A Wisconsin pilot project. Sharon Long, UW-Madison. 7/1/2014 -6/30/16. Department of Natural Resources. \$61,052.

Monitoring and modeling support for groundwater management and policy in the Wisconsin Central Sands. George Kraft, UW-Stevens Point. 7/1/2014 -6/30/16. Department of Natural Resources. \$45,270.

Describing connected fracture flow with pressure waves – oscillating flow interference testing. Michael Cardiff, UW-Madison. 7/1/15-6/30/17. Department of Natural Resources. \$63,670.

Evaluation of Quantitative Real Time PCR (qPCR) for the Measurement of E. coli in Well Water Samples. Greg Kleinheinz, Nilay Sheth, UW-Oshkosh. 7/1/15-6/30/16. Department of Natural Resources. \$ 31,548.

TOTAL - \$537,487

Beginning in 2010, WRI's annual 104(B) allocation was used to expand the scope of the Joint Solicitation to include research on the effects of climate change on Wisconsin's water resources. Priorities for climate change research were established through a partnership between the WRI and the Wisconsin Initiative on Climate Change Impacts (WICCI). Established in 2007, WICCI is a university-state partnership created to: (a) assess and anticipate the effects of climate change on specific Wisconsin natural resources, ecosystems and regions; (b) evaluate potential effects on industry, agriculture, tourism and other human activities; and (c) develop and recommend adaptation strategies that can be implemented by businesses, farmers, public health officials, municipalities, resource managers and other stakeholders. We believe these partnerships with other state agencies provides WRI with the ability to fund highly relevant research and allows our limited funds for 104(B) to be leveraged to the fullest extent. WRI has funded five research projects related to these priorities since 2010; two of these projects are included in this year's annual 104(B) report (Larson and Underwood, Choi and Wu). WRI is now sponsoring WICCI's phase 2 with the goal of advancing climate adaptation projects related to water resources challenges in Wisconsin.

# Climate Change Impacts on Stream Temperature and Flow: Consequences for Great Lakes Fish Migrations

## Basic Information

<b>Title:</b>	Climate Change Impacts on Stream Temperature and Flow: Consequences for Great Lakes Fish Migrations
<b>Project Number:</b>	2011WI267B
<b>Start Date:</b>	3/1/2014
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	WI-2
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Climatological Processes, Ecology, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Peter Biek McIntyre

## Publications

1. Childress, Evan, J. David Allan, Peter McIntyre; In Press; Nutrient subsidies from native fish migrations enhance productivity in Great Lakes tributaries. *Ecosystems* Vol. 17. 12 pg.
2. McIntyre PB, C. Reidy Liermann, E. Childress, E.J. Hamann, J. Hogan, S.R. Januchowski-Hartley, A.A. Koning, T.M. Neeson, D.L. Oele, B.M. Pracheil. In Press. Conservation of migratory fishes in freshwater ecosystems. *Conservation of Freshwater Fishes*
3. Childress, Evan, J. David Allan, Peter McIntyre; In Press; Nutrient subsidies from native fish migrations enhance productivity in Great Lakes tributaries. *Ecosystems* Vol. 17. 12 pg.
4. McIntyre, PB, C Reidy Liermann, E Childress, EJ Hamann, J Hogan, SR Januchowski-Hartley, AA Koning, TM Neeson, DL Oele, BM Pracheil. 2015. Conservation of migratory fishes in freshwater ecosystems. In: Closs G, Krkosek M, & Olden JD: *Conservation of Freshwater Fishes*. Cambridge University Press, Cambridge, UK.
5. Childress, E.S. and P.B. McIntyre. 2015. Multiple nutrient subsidy pathways from a migration of iteroparous fishes. *Freshwater Biology* 60: 490-499.
6. Childress, E.S., R. Papke, and P.B. McIntyre. 2015. Spawning success and early life history of longnose suckers in Great Lakes tributaries. *Ecology of Freshwater Fish* doi: 10.1111/eff.12220.
7. Childress E., J.D. Allan, and P.B. McIntyre. 2014. Nutrient subsidies from iteroparous fish migrations can enhance stream productivity. *Ecosystems* 17:522-534. Doi: 10.1007/s10021-013-9739-z.
8. McIntyre, P.B., C. Reidy Liermann, E. Childress, E.J. Hamann, S.R. Januchowski-Hartley, A.A. Koning, T.M. Neeson, D.L. Oele, and B.M. Pracheil. 2016. Conservation of migratory fishes in freshwater ecosystems. Pp. 324-360. In: Closs, G.P., M. Krkosek, and J.D. Olden (eds.): *Conservation of Freshwater Fishes*. Cambridge University Press. Cambridge, United Kingdom.
9. Lyons J, A.L. Rypel, P.W. Rasmussen, T.E. Burzynski, B.T. Eggold, J.T. Myers, T.J. Paoli, and P.B. McIntyre. 2015. Trends in the reproductive phenology of two Great Lakes fishes. *Transactions of the American Fisheries Society* 144:1263-1274. DOI: 10.1080/00028487.2015.1082502.
10. Childress, E.S., R. Papke, and P.B. McIntyre. 2015. Spawning success and early life history of longnose suckers in Great Lakes tributaries. *Ecology of Freshwater Fish*. doi: 10.1111/eff.12220.

# 2015 Annual Report

**Reporting Period:** 3/1/2014 - 2/28/2015

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## Project

WR11R002 - Climate Change Impacts on Stream Temperature and Flow: Consequences for Great Lakes Fish Migrations

## Principle Findings and Significance

Objective 1: Quantifying the historical timing of Great Lakes fish migrations in Wisconsin tributaries.

The US Fish and Wildlife Service collected a unique data set as part of their lamprey control program that included data for multiple migratory species over a period of six decades. Our initial analyses indicated that 8 of 13 species showed earlier peak spring migration dates through time. Earlier migration timing is consistent with the hypothesis that ever-warmer spring temperatures are advancing fish spawning phenology.

We are now developing a spatiotemporal Bayesian hierarchical statistical model to quantify shifts in migration timing simultaneously for multiple fish species. We have extracted Julian dates of the first and peak migration for each species in each stream in each year, as well as NOAA's remotely-sensed lake surface temperatures at the mouth of 182 tributaries (1994–2011).

In the past year, our model development has focused on the date of the first fish observation. Rather than relying on a single lake surface temperature measurement, we are defining the cue temperature regime based on the average temperature during 15 days prior to the first migration day. We have extracted that information for white suckers in every stream for 18 years of observations, yielding stream-specific cue regimes of lake surface temperatures. We then use an approach called functional data analysis to identify the time period in each year that most closely resemble the typical temperature cue-regime, and we designate the final day of that period as our estimated Julian date of cue temperature. This approach performs well for most years (see examples in Figure 1).

The analysis reveals a clear trend; the cue temperature regime moves to earlier dates throughout the period from 1995-2011 (Figure 2a). At the same time, the actual migration data indicate earlier onsets over time (Figure 2b). Importantly, merging these two findings shows a statistically significant relationship between the Julian day of actual migration and the Julian day of the cue temperature regime in an individual river (Figure 2c) and across multiple rivers.

We are now working to resolve two additional statistical challenges. First, it is likely that migratory fish are cuing on stream temperatures—for which widespread data since 1950 do not exist—rather than the lake surface temperatures that we have derived from satellite data. Second, the satellite data only cover the period from 1994 to 2012, which excludes much of the available fish migration data. Thus, we have obtained a century-long record of water temperature in the St. Mary's River near the outlet of Lake Superior at Sault St. Marie (SSM), and will create a stream-specific relationship between SSM temperature and our remotely-sensed temperature. That relationship will enable us to estimate the SSM temperature at which the stream-specific cue temperature occurs, and then use

long-term SSM data as a surrogate to estimate the Julian data at which lake surface temperature would cue historical migrations prior to 1994. In this way, we can extend the analysis of migration cue phenology back to 1950, thereby matching the actual records of migration timing. As in Figure 2, this procedure will allow us to test whether phonological shifts are attributable solely to temperature cue timing shifts, or may also reflect other considerations. Moreover, we will then complete the analysis by using Bayesian hierarchical modeling to draw upon the complete space-time mosaic of migration observations to estimate the overall rate of change of migration phenologies in Great Lakes tributaries, and whether it varies systematically in space or across species.

There are no new results from 2014-2015 to report regarding Objectives 2 or 3.

**Number of Personnel Involved**

- 2 Participating faculty/staff
- 1 Supported post-docs

**Students Supported**

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**Name**

Evan Childress

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

Freshwater & Marine Science

**Graduation**

12/2014

**Thesis Title**

Cross-Ecosystem Delivery of Nutrients to Streams: The Role of Fish Migrations and Landscape Processes

**Job Placement**

Government

**Conference Participation**

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**Title**

Society for Conservation Biology

**Location**

Missoula, MT

**Dates**

July 2014

Number of supported students attending

1

Presentations by Staff

Conservation in novel aquatic ecosystems. McIntyre, P.B., E.S. Childress & B. Kraemer

Presentations by Students

Conserving fish migrations for the sake of the stream. Childress, E.S. and P.B. McIntyre

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Title

Joint Aquatic Sciences Meeting (SFS & ASLO)

Location

Portland, OR

Dates

May 2014

Number of supported students attending

1

Presentations by Students

Effects of iteroparous fish migrations in streams. Childress, E.S. and P.B. McIntyre

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Journal Articles and Other Publications

Title

Conservation of Freshwater Fishes (book)

Type of Publication

Brochure, Fact Sheet or Poster (Peer-reviewed)

Complete Citation

McIntyre PB, Reidy Liermann C, Childress E, Hamann EJ, Hogan J, Januchowski-Hartley SR, Koning AA, Neeson TM, Oele DL, & Pracheil BM. 2015. Conservation of migratory fishes in freshwater ecosystems. In: Closs G, Krkosek M, & Olden JD: Conservation of Freshwater Fishes. Cambridge University Press, Cambridge, UK.

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Title

Freshwater Biology

Type of Publication

Book or Monograph (Peer-reviewed)

Complete Citation

Childress, E.S. and P.B. McIntyre. 2015. Multiple nutrient subsidy pathways from a migration of iteroparous fishes. Freshwater Biology 60: 490-499.

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Title

Ecology of Freshwater Fish

Type of Publication

Book or Monograph (Peer-reviewed)

Complete Citation

Childress, E.S., R. Papke, and P.B. McIntyre. 2015. Spawning success and early life history of longnose suckers in Great Lakes tributaries. Ecology of Freshwater Fish doi: 10.1111/eff.12220.

Title

Ecology

Type of Publication

Book or Monograph (Peer-reviewed)

Complete Citation

Childress E & McIntyre PB. Life history traits modulate ecosystem-level effects of nutrient subsidies from fish migrations. Ecology, in review.

Title

Transactions of the American Fisheries Society

Type of Publication

Book or Monograph (Peer-reviewed)

Complete Citation

Lyons J, Rypel AL, Rasmussen PW, Burzynski TE, Eggold BT, Myers JT, Paoli TJ, & McIntyre PB. Trends in the reproductive phenology of two Great Lakes fishes. Transactions of the American Fisheries Society, in revision.

Awards and Achievements

Title

Graduate fellowship

Recipient(s)

Evan Childress

Awarded By

NSF IGERT: Conservation in Novel Ecosystems

Type of Award

Research

Description

Evan received a 2-year graduate fellowship to complete his degree as a fellow of the Novel Ecosystems IGERT based in Forest & Wildlife Ecology at UW-Madison

Student Award?

Yes

Number of students receiving award

4

**Title**  
Malueg Award for Graduate Student Excellence

**Recipient(s)**  
Evan Childress

**Awarded By**  
Center for Limnology

**Type of Award**  
Service

**Description**  
This is the annual award for the graduate student in the CFL who best combines research excellence and community citizenship

**Student Award?**  
Yes

**Number of students receiving award**  
1

**Research Patent or Copyright**  
No research patents or copyrights reported.

**Climate change impacts on stream temperature and flow:  
consequences for Great Lakes fish migrations**

WRI Completion Report

Submitted by Dr. Peter McIntyre, UW-Madison Center for Limnology

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## Project Summary

**Title:** Climate change impacts on stream temperature and flow: consequences for Great Lakes fish migrations

**Project ID:** WR11R002

**Investigator:** Peter McIntyre, Assistant Professor, Center for Limnology; Evan Childress, PhD student, Freshwater & Marine Sciences

**Period of Contract:** March 1, 2011 through February 29, 2016

**Background/Need:** Having achieved consensus that Wisconsin's air and water are warming under global climate change (<http://www.wicci.wisc.edu/>), a key challenge now is to understand the breadth of ecological impacts. Wisconsin citizens benefit greatly from the services provided by water resources, and fisheries have particular cultural importance. Present understanding of climate warming impacts on fish is based largely on thermal tolerances; effects on breeding behavior and success are poorly known. Many important fish species migrate from the Great Lakes into tributaries to breed every year, and potential cues for these migrations (temperature, flow) are being altered by climate change. However, historical rates of change in migration timing are unknown, the abiotic triggers of migrations remain uncertain, and ecosystem responses to fish migrations have not been determined. *This project addresses needs for both scientific and public understanding of climate-driven shifts in the timing of Great Lakes fish migrations, and their ecological implications.*

**Objectives:** *Objective 1:* Quantify the historical timing of Great Lakes fish migrations into Wisconsin tributaries. *Objective 2:* Monitor the current migration timing along a latitudinal gradient of Wisconsin tributaries to identify threshold temperature and flow levels that trigger the onset of migrations. *Objective 3:* Predict how the timing of migrations is likely to shift with future climate change, and evaluate the implications from species to ecosystems.

**Methods:** To assess long-term trend in the timing of fish migrations across decades for a large number of US tributaries of the Great Lakes, we mined the US Fish and Wildlife Service's sea lamprey electric barrier data for the period 1950-2011. These data include daily (or nearly) records during the spring season for ~150 watersheds. However, few observation sets extend >20 years in a single watershed. To take advantage of the spatial extent of these data while minimizing the limitations arising from short time series per site, we developed a flexible Bayesian hierarchical spatial regression model that quantifies spatial and temporal trends. The model has two levels: a lower one that models the temporal trend in migration at each tributary, and an upper one that models the spatial variation in the trends, thereby accounting for spatial autocorrelation. The Julian day on which the maximum number of fish was observed provides an index of timing, and we analyzed the anomaly from the long-term average for each stream. Our work to date has focused on migratory species: white sucker and sea lamprey.

To understand the cues triggering migrations, we worked with Wisconsin DNR to identify 12 local citizens who recorded the arrival of suckers by checking a road crossing daily at a single stream in 2011 and 2012. We measured daily temperature and discharge in each stream, enabling us to analyze migration timing with respect to latitude, temperature, and discharge.

We planned to combine ecosystem monitoring and projections of stream flow and temperature to assess the future timing and significance of migrations. Unfortunately, our USGS partners lost

funding for projections. To understand ecosystem responses to migrations, we conducted detailed studies of migration dynamics, nutrient inputs, stream metabolism, and larval export.

**Results and Discussion:** We found that the timing of fish migrations into Great Lakes tributaries is highly sensitive to water temperature, supporting the possibility that warming waters has and will shift spring migrations toward earlier calendar dates. However, historical migration data reveal more complex phenological shifts. For both suckers and lamprey, some locations are seeing later migrations, while fish are moving earlier in others. Such variability contrasts with general warming of the lake surface near every study stream from 1994-2011. Historical records of stream temperatures during the spring are not available for most streams, making it difficult to resolve the basis for complex shifts in timing. However, parallel work on lake-spawning species also indicates variable effects on reproductive phenology.

Our citizen science network provided evidence that tributary temperature, not flow or lake temperature, is the salient migration cue for suckers. The observed offset of migrations by ~10 days between southern and northern Wisconsin echoes differences in spring warming of streams. Since stream temperatures track air temperatures, this form of cue has likely shifted across the region by days-to-weeks over the last century. Equally importantly, our work offers the first proof that citizen science can yield useful data on fish migration phenology.

We found strong evidence that migrations are key events in tributary ecosystem dynamics. As thousands of suckers spawn and leave during a month-long run, they provide nitrogen and phosphorus. These nutrients boost primary productivity, benefitting all stream biota. Larval suckers pour out of river mouths in synchrony, creating a major food resource for predatory fishes. Thus, these migrations play a key role in the annual productivity cycle of the ecosystem.

**Implications:** Though the timing of spawning migrations is changing in the Great Lakes, the direction and magnitude of shifts is complex. Changes are expected to continue into the future, potentially decoupling critical ecosystem processes that were previously synchronized. Such phenological decoupling is a subtle yet profound threat to fisheries and ecosystem sustainability.

#### **Related Publications:**

- Childress E & McIntyre PB. 2016. Life history traits modulate ecosystem-level effects of nutrient subsidies from fish migrations. *Ecosphere*, in press.
- Childress ES, Papke R, & McIntyre PB. 2016. Reproductive success and early life history of suckers in Great Lakes tributaries. *Ecology of Freshwater Fish*, in press.
- Childress E, & McIntyre PB. 2015. Multiple nutrient subsidy pathways from a spawning migration of iteroparous fish. *Freshwater Biology* 60: 490-499.
- Lyons J, Rypel AL, Rasmussen PW, Burzynski TE, Eggold BT, Myers JT, Paoli TJ, & McIntyre PB. 2015. Trends in the reproductive phenology of two Great Lakes fishes. *Transactions of the American Fisheries Society* 144 1263-1274.
- McIntyre PB, Reidy Liermann C, Childress E, Hamann EJ, Hogan J, Januchowski-Hartley SR, Koning AA, Neeson TM, Oele DL, & Pracheil BM. 2015. Conservation of migratory fishes in freshwater ecosystems. In Closs G, Krkosek M, & Olden JD: *Conservation of Freshwater Fishes*. Cambridge University Press, Cambridge, UK.

**Key Words:** phenology, sucker, subsidy, nutrients, potamodromous, metabolism

**Funding:** WR11R002

## INTRODUCTION

Having achieved consensus that Wisconsin's air and water are warming under global climate change (<http://www.wicci.wisc.edu/>), a key challenge for scientists now is to understand the breadth of ecological impacts of climate change. Wisconsin citizens benefit greatly from the numerous services provided by our water resources, and fisheries have particular cultural importance. Present understanding of the likely effects of climate warming on fish ecology and fisheries productivity is based largely on studies of thermal tolerances; little attention has been directed toward impacts on the breeding behavior and success of important fish species. Many of the key sportfish and non-game fishes of Wisconsin migrate from lakes and large rivers into tributaries to breed every year. These migrations are triggered by temperature or flow cues whose reliability and timing are being altered by climate change. Several initiatives are underway to forecast shifts in these abiotic conditions, but the implications for the future of fish migrations and the host of ecological and economic processes they support are unknown. Moreover, the public at large struggles to understand the value of research on the physicochemical effects of climate change. The abiotic-biotic coupling underlying fish migrations offers an ideal opportunity for outreach that leverages broad public interest in fish and fisheries. *Thus, this project addressed needs for both scientific and public understanding of the ecological impacts of climate-driven shifts in water temperature and flow using the timing of Great Lakes fish migrations as a case study.*

## PROCEDURES AND METHODS

*Objective 1: To obtain a historical context for the timing of fish migrations, and to assess long term trends across decades for a large number of US tributary rivers.* The US Fish and Wildlife Service collected a unique data set as part of their lamprey control program that included data for multiple migratory species over a period of six decades. Our initial analyses indicated that 8 of 13 species showed earlier peak spring migration dates through time. Earlier migration timing is consistent with the hypothesis that ever-warmer spring temperatures are advancing fish spawning phenology. However, this pilot analysis suffered from low sample size at most sites.

To make best use of the incomplete matrix of observations across sites and years, we developed a flexible Bayesian hierarchical statistical model to quantify shifts in migration timing simultaneously across sites. This approach draws strength from the breadth and duration of observations to inform inferences at any one site even in the absence of direct data. Our analyses span a total of 182 tributaries from 1950–2011, though few observation sets extend >20 years in a single watershed. The model has two levels: a lower one that models the temporal trend in migration at each tributary, and an upper one that models the spatial variation in the trends, thereby accounting for spatial autocorrelation. Initial model development focused on the date of the first fish observation, but we discovered that this appears to be biased by variation in when observations began each year. Thus, we focused solely on the timing of maximum migrant densities for white suckers and sea lamprey, the two most abundant species in the dataset. We used the anomaly from the long-term average for each stream to standardize observations across sites before analysis.

Rather than relying on a single lake surface temperature measurement to identify the migration cue, we defined the cue temperature regime based on the average temperature during 15 days prior to the first migration day. We extracted that information for white suckers in every stream for years where remote sensing data allowed it, then used functional data analysis to identify the time period in every year of fish observations that most closely resemble the typical temperature

regime to trigger a migration. The final day of that period was designated as the estimated Julian date of cue temperature.

*Objective 2: To identify the cues that trigger fish migrations using data derived from a citizen science network of observers in Wisconsin.* Citizen science is an effective way to engage citizens and educate them about the local impacts of climate change. Additionally, it provides a mechanism for collecting data simultaneously across a broad geographic range. We established a volunteer monitoring network to observe the sucker migration along the Wisconsin shore of Lake Michigan to determine the current migration phenology and evaluate migration cues. Suckers were chosen because they are ubiquitous, abundant, and easily identifiable. We collaborated with the WDNR and UW Extension volunteer monitoring program to identify and contact potential volunteers. The USGS provided stream gauges that were installed in each stream along with a temperature logger. Each volunteer was trained in fish identification, and an observation site was chosen to maximize visibility and convenience.

In 2011, 20 volunteers monitored sucker arrival, temperature, and flow levels in 15 tributaries spanning over 200 miles of Lake Michigan shoreline. In 2012, volunteers were again prepared to monitor, but unfortunately the fish arrived two months prior to the 2011 arrival date. Thus, our citizen monitoring had not yet been initiated when most migrations began, and we were unable to replicate the 2011 results. Nonetheless, data on phenology were collected opportunistically at a few northern Wisconsin streams where the migration had not yet begun, and in Green Bay through others project within our broader research team. We did not attempt to reinstate citizen science monitoring in 2013 due to the need to pursue other project elements.

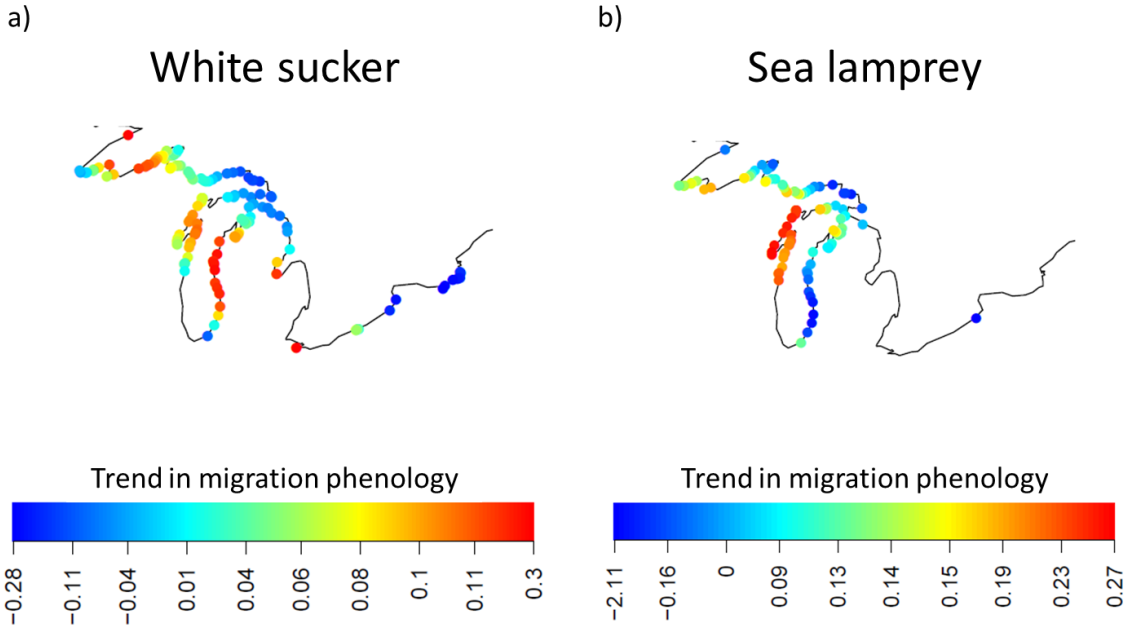
*Objective 3: To predict how the timing of migrations is likely to shift with future climate change, and evaluate the implications from species to ecosystems.* This project element was envisioned to include collaboration with USGS researchers on projecting future stream flow and temperature patterns, as well as field research to quantify ecosystem responses to spring fish migrations. Projections were not possible due to funding cuts to our colleagues at the USGS Wisconsin Water Science Center, therefore we focused on measuring ecosystem dynamics during migrations to understand the broader effects of shifting phenologies.

During the spring migrations in 2012 and 2013, we conducted a series of detailed studies on stream metabolism (measured using time series of oxygen dynamics), nutrient inputs (measured using water samples), algal growth limitation by light and nutrients (using nutrient diffusing substrates), and larval sucker production (using drift nets).

## **RESULTS AND DISCUSSION**

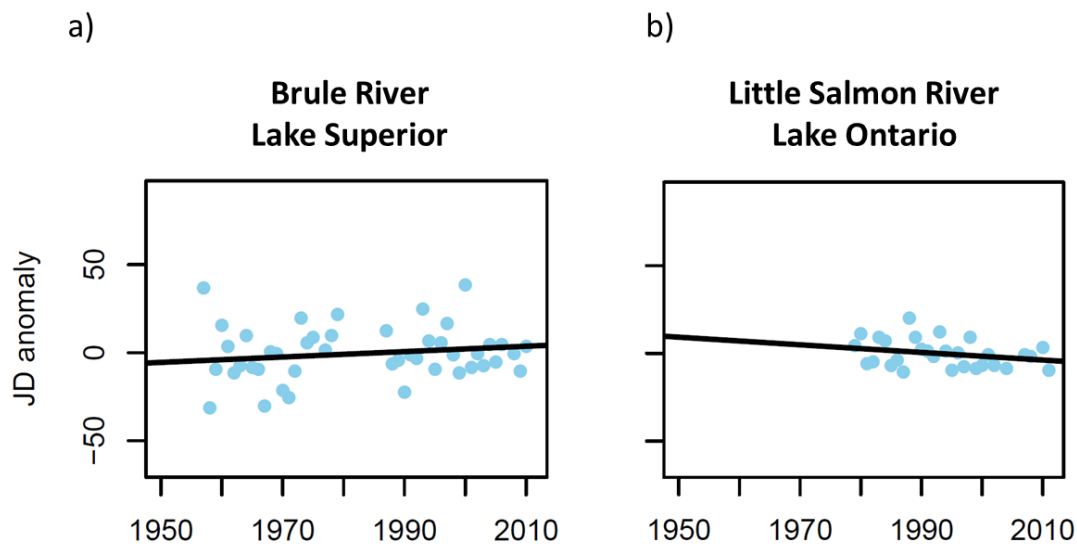
### **Historical phenologies**

Based on lake surface temperature data, the cue temperature regime moved to earlier dates throughout the period from 1995-2011 in most streams, suggesting that fish should be shifting to earlier migration timing across the Great Lakes. However, the actual migration data indicate both positive and negative trends in peak migration timing from 1950-2011 for both white suckers and sea lamprey (Figure 1). There are geographic patterns evident, though they defy simple summary.



**Figure 1.** Spatial variation in the trend of migration timing for both species. The colour of each location reflects how many days per year the migration is changing. On a decadal scale, a coefficient of 0.3 indicates a change of 3 days per decade. Negative numbers in blue indicate a trend toward earlier migrations, while positive numbers in red indicate a trend toward later migrations.

Our statistical model, the most complete and sophisticated to date, suggests extensive heterogeneity in fish responses to climate change. Specifically, it is noteworthy that suckers and lamprey in some regions appear to show strong shifts to later spring migrations, despite consistent warming of lake temperatures (Figure 2). Further analyses are ongoing, therefore we consider the current patterns to be preliminary.

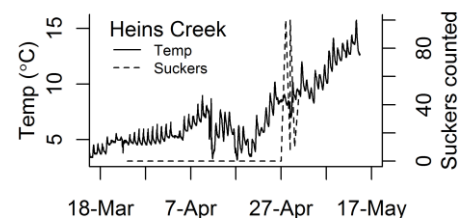


**Figure 2.** Scatter plots of Julian Day of the peak of migration at two rivers, each showing distinctive temporal trends. Brule River is located toward the western edge of Lake Superior, while the Little Salmon River on Lake Ontario is located on the eastern shores of the lake in New York.

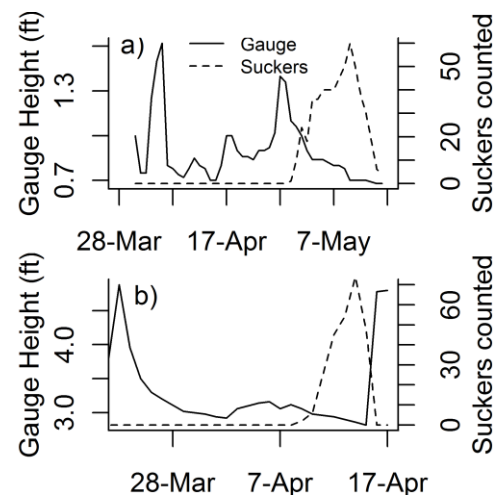
The disparity between lake temperature trends fish migration timing underscores the need for better stream temperature data. We have recently received four stream temperature records (1950s to present) from USGS that we were unaware of, and we will couple these with the century-long record from the outlet of Lake Superior at Sault St. Marie to assess whether this heterogeneity derives from stream temperature shifts that diverge from lake temperature shifts. Our Bayesian hierarchical model will then enable us to draw upon the space-time mosaic of migration observations while also accounting for spatially variable shifts in stream temperatures. We have not completed these analyses yet, but they will provide a state of the art perspective on rates of change in fish migration timing. If the approach is successful for white suckers and sea lampreys, we will repeat it for all other species in the database (e.g. walleye).

### Migration cue determination through citizen science

Our citizen science results from 2011 indicated that sucker arrival timing was closely linked with temperature but showed no clear pattern relative to flow. Mean temperature on the day of the first pulse of fish was 7.6° C (SD = 0.6) (e.g., Fig. 3). Despite the variability among sites in the start date of the migration, water temperatures at the start of the migration were highly consistent. In contrast, fish arrival was not associated with any particular hydrograph component. In some streams, fish arrived during high flows, but in others they arrived after long periods of declining flows (Fig. 4). This indicates that migration timing depends primarily on water temperature.



**Figure 3.** Example of the timing of sucker migrations relative to stream temperature in 2011.



**Figure 4.** Examples of the timing of sucker migrations relative to stream discharge in (a) Fish Creek and (b) Oak Creek in 2011.

### Ecosystem effects of sucker migrations

We found strong evidence that migrations are key events in tributary ecosystem dynamics. As many as 12,000 suckers may spawn in a single small stream, though there is extensive variation among watersheds. The size of runs does not accord clearly with watershed area or tributary discharge, and we also observed moderate interannual variation. The reasons for these differences remain unknown.

As thousands of suckers spawn and leave during a month-long run, they significantly elevate stream nitrogen concentrations (Figure 5). Interestingly, we calculate that phosphorus must be provided as well, but concentration data show little consistent evidence of boosted availability of phosphorus.

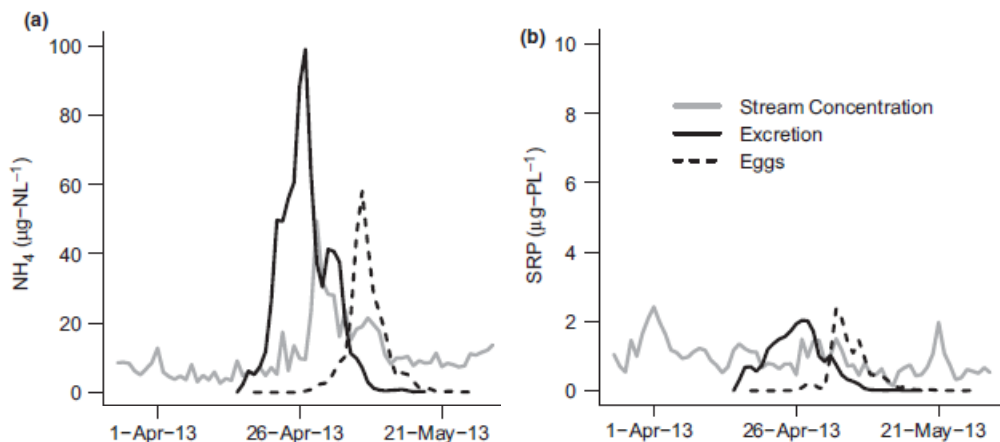


Figure 5. Dynamics of nutrient inputs via nutrient excretion (black line) and eggs (dashed line) relative to observed stream concentrations of nitrogen (a) and phosphorus (b). Stream concentrations of nitrogen and phosphorus remained unchanged in a reference stream with no fish migration.

Our nutrient diffusing substrate experiments indicate that algal growth is enhanced primarily by added phosphorus, sometimes with secondary benefits of adding nitrogen (Figure 6). This experiment indicates that fish migrations are likely to boost ecosystem productivity to the degree that they provide a source of phosphorus in bioavailable chemical form.

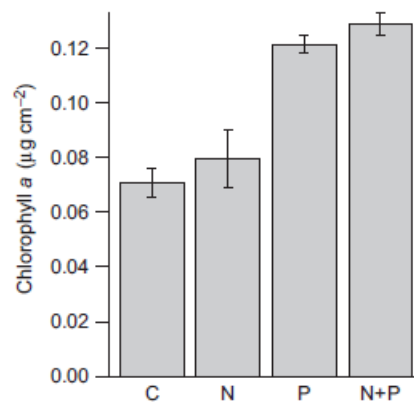


Figure 6. Response of algae to experimental additions of nitrogen only (N), phosphorus only (P), both N and P, or no nutrients (C).

Monitoring of whole-ecosystem metabolism confirms that large sucker runs enhance the productivity of the entire stream (Figure 7). This is the first strong demonstration of an ecosystem-level response to nutrients from a repeat-spawning fish species. Our results compliment those from salmon, but differ in important ways. Salmon both die after spawning and excavate large patches of substrate before laying eggs. Both factors elevate the breakdown of organic matter in the stream, and suppress algal growth. Thus, salmon streams typically see a decrease in ecosystem primary productivity during the migration, whereas we find that suckers boost gross primary productivity. Conversely, salmon enhance ecosystem respiration, whereas suckers cause only slight increases in respiration during their migration.

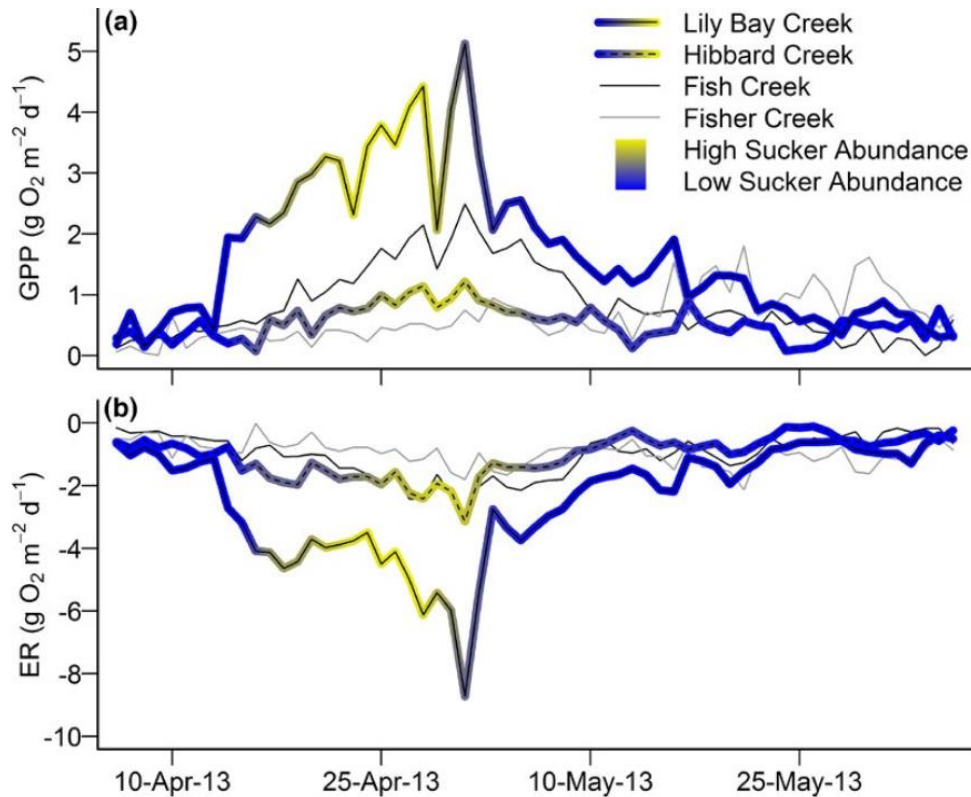


Figure 7. Ecosystem metabolism patterns in four streams in 2013. Colored lines indicate streams where migratory suckers were spawning. Grey lines indicate streams where fish could not gain access. Line color indicates the abundance of fish measured in each stream, from high (yellow) to low (blue).

The boost to ecosystem productivity arising from sucker migrations is likely to benefit all stream biota. We observed juvenile rainbow trout gorging on sucker eggs in 2012, but our attempt to study that relationship in 2013 was prevented by mass mortality of trout during the hot summer of 2012. After hatching, larval suckers pour out of river mouths in synchrony, entering the Great Lakes in enormous numbers. These emigrating larvae represent just a tiny fraction of the eggs laid, yet are still abundant enough to provide a major food resource for predatory fishes (Figure 8). Indeed, every year we would observe rock bass, creek chubs, yellow perch, and other species gather at stream mouths to take advantage of this resource pulse. Taken together, our findings indicate that migrations of native fishes into tributaries play a key role in the annual productivity cycle of both the streams and the Great Lakes.

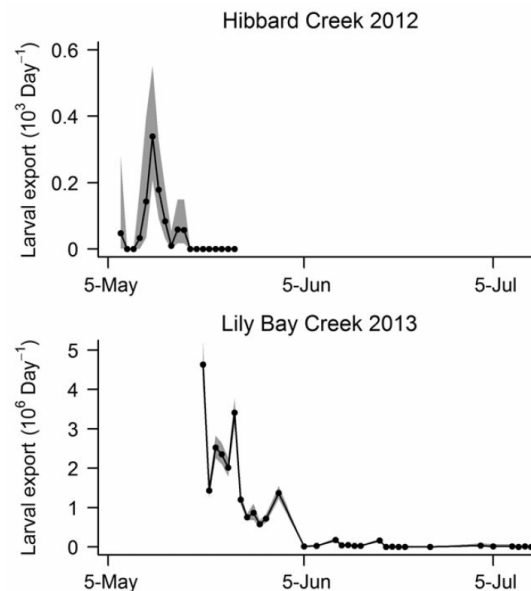


Figure 8. Emigration of sucker larvae from study streams in Door County through time. Lines represent observed dynamics; grey areas are confidence intervals estimated by bootstrapping.

## CONCLUSIONS AND RECOMMENDATIONS

Though the timing of spawning migrations is changing in the Great Lakes, the direction and magnitude of shifts is complex. This complexity is quite different from reported patterns in the handful of other freshwater ecosystems where migration timing has been studied. In all other published cases, fish are moving earlier in the spring or later in the fall, in keeping with expectations from warming patterns and temperature-cued migrations. We observed that lake-based temperature cue regimes are indeed shifting forward in the spring, but fish appear to be responding in complex ways.

With continued or accelerating warming in the future, there is reason for concern about how changes in the timing of inputs of nutrients and larvae could affect ecosystem dynamics. If the growth of algae and insects shifts at the same pace as the timing of fish migrations, the effects may be minimal. However, as fish-associated nutrient inputs become earlier in the year, the amount of light energy available to support algal growth will be reduced because day length is independent of thermal regimes. Moreover, the shading of streams by budburst of trees is expected to shift with climate warming, but responding to a very different set of cues than tributary-spawning fishes. Similarly, the migratory birds that depend on the emergence of stream insects to refuel as they move northward in the spring may well arrive out of sync with their prey. These examples of phenotypic decoupling are troubling, though much more research is required to assess their likelihood and expected effects.

Groundwater resources will play a special role in future patterns of fish migration phenology. Groundwater flows and temperatures are far less influenced by air temperature than surface flows. Thus, groundwater inputs to tributary streams has a unique capacity to buffer them against climate change, at least over the short term. Great Lakes tributaries vary widely in the proportion of their flow derived from groundwater, which may be part of the explanation for the spatial heterogeneity that we observed in rates of change of migration timing. Should groundwater flows be reduced, rates of stream warming would almost certainly increase, leading to even earlier spring fish migrations.

This project has also served as a pilot exploration for developing a citizen science network to monitor migratory fish phenology in the Great Lakes region. We learned that this approach can yield high-quality data, but requires sufficient staff support to maintain intensive communication with the network of volunteers. In addition, our failure in 2012 to cover the migration season arose from the time lag involved in launching volunteer monitoring efforts anew each year. These lessons will be incorporated into plans for a much larger, sustained citizen-based phenology monitoring network being co-developed by Shedd Aquarium and UW-Madison Center for Limnology. Only citizen scientists can offer sufficiently broad coverage of Great Lakes watersheds to enable robust inferences about spatial patterns in migration timing. As we begin to seek funding to launch this new effort, the experience gained under this project will be invaluable.

## APPENDIX A

### Publications accepted

Childress E & McIntyre PB. 2016. Life history traits modulate ecosystem-level effects of nutrient subsidies from fish migrations. *Ecosphere*, in press.

Childress ES, Papke R, & McIntyre PB. 2016. Reproductive success and early life history of suckers in Great Lakes tributaries. *Ecology of Freshwater Fish*, in press.

Childress E, & McIntyre PB. 2015. Multiple nutrient subsidy pathways from a spawning migration of iteroparous fish. *Freshwater Biology* 60: 490-499.

Lyons J, Rypel AL, Rasmussen PW, Burzynski TE, Eggold BT, Myers JT, Paoli TJ, & McIntyre PB. 2015. Trends in the reproductive phenology of two Great Lakes fishes. *Transactions of the American Fisheries Society* 144 1263-1274.

McIntyre PB, Reidy Liermann C, Childress E, Hamann EJ, Hogan J, Januchowski-Hartley SR, Koning AA, Neeson TM, Oele DL, & Pracheil BM. 2015. Conservation of migratory fishes in freshwater ecosystems. In Closs G, Krkosek M, & Olden JD: *Conservation of Freshwater Fishes*. Cambridge University Press, Cambridge, UK.

### Publications in review or preparation

Mason LA, Riseng CM, Gronewold AD, Rutherford ES, Wang J, Clites A, Smith SDP, & **McIntyre PB**. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change*, in review.

Moerke A, David S, Childress E & McIntyre PB. Dynamics of spring fish migrations in northern Lake Michigan. *Freshwater Science*, in preparation.

David S, Moerke A, Herbert M, Khoury M, Moody A, Neeson T & McIntyre PB. Phylogenetic and ecological diversity of Great Lakes migratory fishes. *Journal of Great Lakes Research*, in preparation.

### Research training

*Evan Childress* – PhD student, Freshwater & Marine Sciences, UW-Madison – [evan.childress@gmail.com](mailto:evan.childress@gmail.com) Evan completed his PhD, and is now a post-doc at the Conte Anadromous Fish Research Station in Massachusetts. During the course of his work, three undergraduates received research internships assisting with our field studies.

*Ben Stewart-Koster* – post-doctoral researcher – [b.stewart-koster@griffith.edu.au](mailto:b.stewart-koster@griffith.edu.au) – Ben has collaborated on this project to construct statistical models of historical timing of migration phenology. He is now a staff scientist at Griffith University, Australia.

*Solomon David* – post-doctoral researcher – [solomon.r.david@gmail.com](mailto:solomon.r.david@gmail.com) – Solomon was a post-doc at the Shedd Aquarium, and collaborated on this project by synthesizing available data on Great Lakes migration timing across dozens of fish species. He is now a staff scientist at the USGS Great Lakes Science Center.

### Impact summary

Our work is boosting awareness of shifts in timing of Great Lakes fish migrations, and their role in tributary ecosystem dynamics. From an ecosystem management perspective, our findings provide new impetus to maximize access of migratory fishes to tributary ecosystems by removing barriers such as dams and impassable road culverts. Doing so can restore natural nutrient inputs, boosting production of the stream insects that feed birds and bats as well as fish that are preyed upon by bears and eagles. From a fisheries standpoint, we have shown that many favored species (walleye, pike,

steelhead) will benefit from both restored spawning ground access and the annual pulse of prey fish derived from migrations of non-game fishes. Along with revealing the complexity of phenological shifts, this project has demonstrated the potential for citizen scientists to aid in documenting the timing of fish migrations at broader spatial scales than researchers alone can achieve. We are now planning a joint initiative between the Shedd Aquarium and UW-Madison Center for Limnology to develop a larger citizen science network for Great Lakes fish migrations that would interface with the USA National Phenology Network (<https://www.usanpn.org/>) and state agency staff to sustain monitoring of fish migration timing.

In addition to our ongoing collaboration with the Shedd Aquarium, we have worked on two other important outreach initiatives. First, we co-organized a major outreach event at the Shedd Aquarium to publicize Great Lakes fish migrations on the first World Fish Migration Day in May 2014. We talked with ~11,000 visitors as they entered and experienced the aquarium, including providing children with a migratory fish ‘passport’ and setting up science show-and-tell tables to talk about methods to track migrations. This event was a huge success, and we just completed the second World Fish Migration Day on May 21, 2014, with equal impact. Both Shedd and UW personnel benefit from this opportunity to leverage our respective resources and talents in the service of public awareness of migrations.

Second, we developed a daily program educating the public about fish migrations, sucker life history, and the impacts of climate change was at the Crossroads at Big Creek Nature Center in spring-summer 2011 and 2012. We prepared a brief lecture for the staff to present to visitors, after which visitors would observe sucker spawning in a local creek on the Center grounds. Brief lectures were given to two volunteer groups about fish migration ecology and climate change. This outreach effort was featured in newsletters for multiple citizen groups, as well as on the WRI Press Room website in August 2011 (<http://wri.wisc.edu/pressroom/Details.aspx?PostID=1138>).

# Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

## Basic Information

<b>Title:</b>	Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change
<b>Project Number:</b>	2011WI268B
<b>Start Date:</b>	3/1/2014
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	WI-2
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Climatological Processes, Water Quality, Geochemical Processes
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Chin H Wu

## Publications

1. Magee M, and CH Wu (In Review) Long-term trends and variability in ice cover and thermal structure in three morphometrically different lakes in response to climate change. Limnology and Oceanography
2. Magee M, and CH Wu (In Review) Hanging climate on three lakes with differing morphometry. Water Research
3. Magee, M. C.H. Wu, D.M. Robertson, R.C. Lathrop, and D.P. Hamilton. 2016. Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers. Hydrology and Earth System Sciences 20:1681-1702. doi:10.5194/hess-2015-488.

# Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

**Reporting Period:** 3/1/2015 - 2/29/2016

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## Project

WR11R003 - Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

## Principle Findings and Significance

The purpose of this study is two-fold: first, to investigate how long-term changes in air temperature and wind speed affect the ice cover and thermal structures of a dimictic Lake Mendota, Wisconsin, USA over the past century; and second, to investigate the role of lake morphometry in long term changes, variability, and sensitivity in response to increasing air temperatures and decreasing wind speeds in the Madison, WI area. Our findings are summarized here.

Observations of the drivers include a change in the trend of warming air temperatures from 0.081 °C per decade before 1981 to 0.334 °C per decade thereafter, as well as a shift in mean wind speed from 4.44 m s<sup>-1</sup> before 1994 to 3.74 m s<sup>-1</sup> thereafter. Using correlation analysis reveals that ice cover variables, stratification onset, epilimnetic temperature, and hypolimnetic temperature were most closely correlated with air temperature, whereas freeze-over water temperature, hypolimnetic heating, and fall turnover date were more closely correlated with wind speed. Each lake variable (i.e., ice-on and ice-off dates, ice cover duration, maximum ice thickness, freeze-over water temperature, stratification onset, fall turnover date, stratification duration, epilimnion temperature, hypolimnion temperature, and hypolimnetic heating) was averaged for the three periods (1911-1980, 1981-1993 and 1994-2014) delineated by abrupt changes in air temperature and wind speed. Average summer hypolimnetic temperature and fall turnover date exhibit significant differences between the third period and the first two periods. Changes in ice cover (ice-on and ice-off dates, ice cover duration, and maximum ice thickness) exhibit an abrupt change after 1994, which was related in part to the warm El Niño winter of 1997–1998. Under-ice water temperature, freeze-over water temperature, hypolimnetic temperature, fall turnover date, and stratification duration demonstrate a significant difference in the third period (1994–2014), when air temperature was warmest and wind speeds decreased rather abruptly.

For the study of lake morphometry, epilimnetic temperatures increased, hypolimnetic temperatures decreased, and the length of the stratified season increased for the study lakes due to earlier stratification onset and later fall overturn. Sensible heat flux in all 3 lakes increases over the simulation period while latent heat flux decreases. The shallow study lake had a greater change in latent heat flux and net heat flux, indicating the role of lake depth to surface heat fluxes. Furthermore, Schmidt stability showed a statistically significant increasing trend for both deep lakes, with the larger trend and greater variability in the larger surface area lake. It is found that the ice cover period has decreased due to earlier ice-on dates and later ice-off dates, and the maximum ice cover thickness has decreased for the three lakes during the last century. Based upon perturbations of air temperatures across the range of -10 °C to +10 °C of historical values, Fish Lake has the most occurrences of no ice cover and Lake Wingra still remains ice covered under extreme conditions (+10°C).

Overall lake variables are found to respond to both long-term and abrupt changes in meteorological conditions. Perturbing climate drivers showed that increasing air temperature and decreasing wind speed caused earlier stratification onset and later fall overturn. For hypolimnetic water temperature, however, increasing air temperature warmed bottom waters while decreasing wind speed cooled bottom waters. Lake depth impacts the presence of stratification and magnitude of Schmidt stability, while lake surface area drives differences in hypolimnion temperature, hypolimnetic heating, variability of Schmidt stability, and stratification onset and fall overturn dates. Shallow lakes with large surface areas are most resilient to ice cover change.

**Number of Personnel Involved**

- 4 Participating faculty/staff
- 0 Supported post-docs

**Students Supported**

---

**Name**

Madeline Magee

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

physical limnology

**Graduation**

8/2016

**Thesis Title**

Assessment and modeling a suite of inland lakes in Wisconsin under changing climate

**Job Placement**

Government

---

**Name**

Nate Gerdts

**Affiliation**

University of Wisconsin-Madison

**Degree**

MA/MS

**Major/Specialization**

environmental fluid mechanics, limnology

**Graduation**

6/2015

**Thesis Title**

Seasonal evaporation of polymictic and dimictic lakes under changing climate

**Job Placement**

Consulting

**Conference Participation**

---

**Title**

Wisconsin Ecology Symposium

**Location**

Madison, WI,

**Dates**

March 2016

**Number of supported students attending**

60

**Presentations by Students**

Fish kills and oxythermal stress under climate and land use changes Magee, M.R. and Wu, C.H.

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**Title**

American Water Resources Association-Wisconsin Section

**Location**

Wisconsin Dells, WI,

**Dates**

March 10, 2016

**Number of supported students attending**

50

**Presentations by Students**

Fish kills and oxythermal stress under climate and land use changes. Magee, M.R. and Wu, C.H.

---

**Title**

UW-Madison Environmental Engineering seminar

**Location**

Madison, WI

**Dates**

February 2016

**Number of supported students attending**

25

**Presentations by Students**

Impact of climate change on ice cover and thermal structure in response to changing climate. Madeline, M

---

**Title**

American Water Resources Association-Wisconsin Section

**Location**

Oconomowoc, WI,

**Dates**

March 5, 2015

**Number of supported students attending**

50

**Presentations by Students**

Temperature Dosage: A Novel Method for Quantifying Oxythermal Stress in Coldwater Fish Species. Magee, M.R. and Wu, C.H.

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**Journal Articles and Other Publications**

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**Title**

Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers

**Type of Publication**

Book or Monograph (Peer-reviewed)

**Complete Citation**

Magee, M. R., Wu, C. H., Robertson, D. M., Lathrop, R. C., and Hamilton, D. P.. 2016 Hydrology and Earth System Science, doi:10.5194/hess-2015-488. <http://www.hydrol-earth-syst-sci-discuss.net/hess-2015-488/> Impact factor 4,292

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**Title**

Effects of changing climate on ice cover in three morphometrically different lakes.

**Type of Publication**

Book or Monograph (Peer-reviewed)

**Complete Citation**

Magee, M.R. and Wu, C.H., Hydrological Processes, accepted under minor revision, March 2016

---

**Title**

Response of water temperature and stratification to changing climate in three lakes with different morphometry

**Type of Publication**

Book or Monograph (Peer-reviewed)

**Complete Citation**

Magee, M.R. and Wu, C.H, International Journal of Limnology, in reviewe

## Awards and Achievements

No awards and achievements reported.

## Research Patent or Copyright

No research patents or copyrights reported.

## Completion Summary

Changes in meteorological factors over the past 104 years were examined on Lake Mendota to determine if there have been abrupt shifts, rather than linear changes. Based on a change in the trend of air temperature increase occurring in 1981 and a major shift in wind speed in 1994, the Madison climate is divided into three distinct periods: 1911–1980, with relatively low air temperatures and mean wind speeds of 4.44 m s<sup>-1</sup>; 1981–1993, with higher air temperatures and mean wind speeds of 4.44 m s<sup>-1</sup>; and 1994–2014 with still higher air temperatures and mean wind speed of 3.74 m s<sup>-1</sup>. Ice cover duration exhibited a significant difference in the mean among all three periods, while ice-on, ice-off, and maximum ice thickness only show a significant difference between period one and three, indicating that only with a large change in air temperature and an abrupt shift in wind speeds are change in the ice cover variables statistically different. Mid-summer hypolimnetic temperature and fall turnover date both reveal significant ( $p < 0.05$ ) differences in the mean value in 1994, corresponding with the abrupt shift toward lower wind speeds. Some lake variables (under-ice water temperature, freeze-over water temperature, epilimnion-hypolimnion temperature difference, and stratification duration) may not be driven by either the change in air temperature trend or the abrupt shift in wind speed alone, but a shift in the mean of the lake variables does occur in 1994 when both the air temperatures are warmest and the wind speed experienced an abrupt shift. The exact timing of shifts may be difficult to define because of extreme changes in weather in specific years and it may mask the longer term changes in meteorological conditions (i.e. abrupt shifts).

Analysis of ice cover on three different study lakes indicates that shallow lakes, such as Lake Wingra, are more resilient to changes in air temperature than their deeper counterparts. Even under extreme increases in air temperature, model results indicate that Lake Wingra will still have ice cover, whereas the deeper Fish Lake and Lake Mendota will not. Since the shallow depth in Lake Wingra facilitates heat loss more quickly during the winter, causing ideal conditions for ice cover even under extreme warm air temperatures. Additionally, lakes with large surface areas can cool more quickly through wind mixing, which allows for easier ice formation on those lakes compared to lakes of similar depth with smaller surface areas. Overall, shallow lakes with large surface areas are most resilient to ice cover changes caused by climate and deep lakes with small surface areas are the least resilient to climate-induced ice cover changes.

Overall, lake depth and lake surface area impact the changing thermal structure in response to climate change. Fish Lake has a much earlier average stratification onset and later fall overturn because of its smaller surface area and less wind-mixing, and the effects of the changing trend is more immediate due to the already long stratified period. A larger magnitude of trend for these changes is shown in Lake Mendota, indicating that larger and deeper lakes are more susceptible to changing climate. Lake Mendota experienced greater variability in stability between high and low air temperature and high and low wind speed years than Fish Lake, suggesting that stability in the larger surface area is more susceptible to changes in the climate variables than in the lake with smaller surface area.

# Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

Final report submitted to the Wisconsin Water Resources  
Institute

April 22, 2016

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## Project Summary

**Title:** Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

**Project I.D:** WR11R003

**Investigator(s):** Principal Investigator – Chin Wu, Professor, Department of Civil and Environmental Engineering. Research Assistants – Madeline Magee, Graduate Research Assistant, Department of Civil and Environmental Engineering

**Period of Contract:** 03/01/2011 ~ 02/29/2015

**Background/Need:** Many studies have shown that lake temperatures and ice cover can strongly affect water chemistry, individual organism physiology, population abundance, community structure, and food-web dynamics. Air temperature and wind speed are important factors driving these lake ecosystem properties. Understanding how lakes respond to changes in these drivers is of great interest to predict how lakes may change in the future. The response of lake ice and water temperature to long-term changes in air temperature and wind speed is integral to assess potential impacts of climate change on lake ecology.

**Objectives:** The purpose of this study is two-fold: first, to investigate how long-term changes in air temperature and wind speed affect the ice cover and thermal structures of a dimictic Lake Mendota, Wisconsin, USA over the past century; and second, to investigate the role of lake morphometry in long term changes, variability, and sensitivity in response to increasing air temperatures and decreasing wind speeds in the Madison, WI area. We hypothesize that changes in lake ice cover and thermal structures on Lake Mendota may be characterized by periods of abrupt changes rather than gradual trends based on observations of rapid change in the climate drivers of air temperature and wind speed. Our second hypothesis is that long term trends of changes in lake ice cover and thermal structure variables will be dependent on differences in lake morphometry (i.e. lake depth and surface area).

**Methods:** To address the research questions, a one-dimensional hydrodynamic model with ice cover is employed to simulate long term (1911-2014) ice cover and water temperature on Lake Mendota, Fish Lake, and Lake Wingra for both historical and future climate scenarios.

### Results and Discussion:

Observations of the drivers include a change in the trend of warming air temperatures from 0.081 °C per decade before 1981 to 0.334 °C per decade thereafter, as well as a shift in mean wind speed from 4.44 m s<sup>-1</sup> before 1994 to 3.74 m s<sup>-1</sup> thereafter. Correlation analysis of lake variables and driving variables revealed ice cover variables, stratification onset, epilimnetic temperature, and hypolimnetic temperature were most closely correlated with air temperature, whereas freeze-over water temperature, hypolimnetic heating, and fall turnover date were more closely correlated with wind speed. Each lake variable (i.e., ice-on and ice-off dates, ice cover duration, maximum ice thickness, freeze-over water temperature, stratification onset, fall turnover date, stratification duration, epilimnion temperature, hypolimnion temperature, and hypolimnetic heating) was averaged for the three periods (1911-1980, 1981-1993 and 1994-2014) delineated by abrupt changes in air temperature and wind speed. Average summer hypolimnetic

temperature and fall turnover date exhibit significant differences between the third period and the first two periods. Changes in ice cover (ice-on and ice-off dates, ice cover duration, and maximum ice thickness) exhibit an abrupt change after 1994, which was related in part to the warm El Niño winter of 1997–1998. Under-ice water temperature, freeze-over water temperature, hypolimnetic temperature, fall turnover date, and stratification duration demonstrate a significant difference in the third period (1994–2014), when air temperature was warmest and wind speeds decreased rather abruptly.

For the study of lake morphometry, we found that during the period, epilimnetic temperatures increased, hypolimnetic temperatures decreased, and the length of the stratified season increased for the study lakes due to earlier stratification onset and later fall overturn. Sensible heat flux in all 3 lakes increases over the simulation period while latent heat flux decreases. The shallow study lake had a greater change in latent heat flux and net heat flux, indicating the role of lake depth to surface heat fluxes. Furthermore, Schmidt stability showed a statistically significant increasing trend for both deep lakes, with the larger trend and greater variability in the larger surface area lake. It is found that the ice cover period has decreased due to earlier ice-on dates and later ice-off dates, and the maximum ice cover thickness has decreased for the three lakes during the last century. Based upon perturbations of air temperatures across the range of -10 °C to +10 °C of historical values, Fish Lake has the most occurrences of no ice cover and Lake Wingra still remains ice covered under extreme conditions (+10°C).

### **Conclusions/Implications/Recommendations:**

The trends in ice cover and water temperature demonstrate responses to both long-term and abrupt changes in meteorological conditions that can be complemented with numerical modelling to better understand how these variables will respond in a future climate. Perturbing climate drivers showed that increasing air temperature and decreasing wind speed caused earlier stratification onset and later fall overturn. For hypolimnetic water temperature, however, increasing air temperature warmed bottom waters while decreasing wind speed cooled bottom waters. Lake depth impacts the presence of stratification and magnitude of Schmidt stability, while lake surface area drives differences in hypolimnion temperature, hypolimnetic heating, variability of Schmidt stability, and stratification onset and fall overturn dates. Shallow lakes with large surface areas are most resilient to ice cover changes caused by climate and deep lakes with small surface areas are the least resilient to climate-induced ice cover changes.

### **Related Publications:**

Magee, M. R., Wu, C. H., Robertson, D. M., Lathrop, R. C., and Hamilton, D. P.. 2016. Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers, *Hydrol. Earth Syst. Sci. Discuss.*, doi:10.5194/hess-2015-488.

Magee, M.R. and Wu, C.H. Effects of changing climate on ice cover in three morphometrically different lakes. *Accepted under revision to Hydrological Processes*

Key Words: climate change, ice cover, stratification, lakes, regime shift

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## Introduction

Many studies have shown that lake temperatures and ice cover can strongly affect water chemistry, individual organism physiology, population abundance, community structure, and food-web dynamics (King et al., 1997; Schindler et al., 1990). Air temperature and wind speed are important factors driving these lake ecosystem properties. Understanding how lakes respond to changes in these drivers is of great interest to predict how lakes may change in the future (Fang and Stefan, 2009). The response of lake ice and water temperature to long-term changes in air temperature and wind speed is integral to assess potential impacts of climate change on lake ecology.

Over the past 100 years, climate has been changing and will continue to change (IPCC, 2013). Globally-averaged combined land and ocean surface temperature data show a linear warming trend of 0.85 °C from 1880–2012 (IPCC, 2013). This warming was most pronounced from 1979–2012, greater than 0.25 °C per decade (Hartmann et al., 2013). Increases in air temperature alter the ice cover of lakes (Butcher et al., 2015; Magnuson et al., 2000; Robertson et al., 1992) and affect their thermal structures (Robertson and Ragotzkie, 1990), evidenced by increasing epilimnetic temperatures (Arhonditsis et al., 2004), warming of the lake surface temperature (Shimoda et al., 2011), increasing temperature gradient across the thermocline (Robertson and Ragotzkie, 1990; Wilhelm and Adrian, 2008), changing thermocline depth (King et al., 1997; Schindler et al., 1990), advancing the onset of summer stratification (Austin and Colman, 2007), delaying fall turnover (King et al., 1997), increasing the strength of thermal stratification (Rempfer et al., 2010), and prolonging the stratified period (Robertson and Ragotzkie, 1990; Wilhelm and Adrian, 2008).

Trends in wind speed over the last 30–50 years have been reported in several studies that have analyzed historical wind speed records across the globe (Wan et al., 2010). Klink (2002) examined 22- to 35-year records (ranging between 1959–1995) of wind speed at seven stations in and around Minnesota and found decreasing annual wind speeds at five of the seven stations. Pryor et al. (2009) reported that the 50<sup>th</sup> and 90<sup>th</sup> percentile annual wind speeds over the period 1973–2005 across most of the U.S. have also decreased. Decreased wind speeds increase thermal stratification and can reduce whole-lake average temperature (Tanentzap et al., 2008). Interestingly, an opposing trend (increasing wind speed) has been observed in Lake Superior, North America, where the lake surface temperatures have been warming faster than air temperatures (Austin and Colman, 2007). Desai et al. (2009) suggest that the larger increase in water temperatures than air temperatures reduced the air-water temperature gradient and destabilized the atmospheric surface layer above Lake Superior, which resulted in increasing wind speed at a rate of nearly 5% per decade. Differences in wind-driven mixing may explain different temperature responses of hypolimnetic waters in large and small lakes (Winslow et al., 2015). While the importance of wind in lake heat transfer (Fu et al., 2009; Read et al., 2012), mixing, and thermal structure (Desai et al., 2009; Schindler et al., 1990) has been recognized, studies on the effects of wind speed alterations on seasonal ice cover and thermal structure of lakes are still rare.

The purpose of this study is two-fold: first, to investigate how long-term changes in air temperature and wind speed affect the ice cover and thermal structures of a dimictic Lake Mendota, Wisconsin, USA over the past century; and second, to investigate the role of lake morphometry in long term changes, variability, and sensitivity in response to increasing air temperatures and decreasing wind speeds in the Madison, WI area. We hypothesize that changes in lake ice cover and thermal structures on Lake Mendota may be characterized by periods of abrupt changes rather than gradual trends based on observations of rapid change in the climate drivers of air temperature and wind speed. Our second hypothesis is that long term trends of changes in lake ice cover and thermal structure variables will be dependent on differences in lake morphometry (i.e. lake depth and surface

area). To address these two questions, a one-dimensional hydrodynamic model with ice cover is employed to simulate long term (1911-2014) ice cover and water temperature on Lake Mendota, Fish Lake, and Lake Wingra for both historical and future climate scenarios.

## Procedures and Methods

### *Study sites*

Three morphometrically different lakes, Lake Mendota, Fish Lake, and Lake Wingra, located near Madison, Wisconsin, USA, were selected for this study (Fig. 1 **Error! Reference source not found.**). These lakes are chosen for (1) their morphometry differences, (2) their close proximity to one another, and (3) the availability of long-term limnological records, which were used for model calibration.

### *Hydrodynamic model*

In this study, a one-dimensional hydrodynamic lake-ice model DYRESM-ICE is used to simulate vertical water temperature distribution and ice cover in Fish Lake, Lake Wingra, and Lake Mendota. Specifically, an ice model is added to the DYRESM-WQ (DYnamic REservoir Simulation Model-Water Quality) model (Hamilton and Schladow, 1997) that simulates vertical water temperature, salinity, and density by using discrete horizontal Lagrangian layers of uniform properties that vary in thickness. The ice model is based upon a quasi-steady state assumption that the time scale for heat conduction through the ice is short relative to the time scale of meteorological forcing. Since sediment heat transfer is important to water temperature beneath ice cover (Ellis et al., 1991), the DYRESM-ICE model used in this study incorporates sediment heat flux, a main external source of lake heating after freezing occurs

### *Analysis*

Multiple statistical methods are used to analyze the results. First, a linear regression is used to determine the trend of long-term changes. A Pearson correlation coefficient (Baron and Caine, 2000) is used to determine the coherence of lake variables (Magnuson et al., 1990) between lake pairs allowing for comparison of correlation of the lake variables to each other. Breakpoints in the air temperature trend over the study period were determined using a piecewise linear regression (PLR) method (Tomé and Miranda, 2004; Toms and Lesperance, 2003; Ying et al., 2015). Abrupt changes in mean annual wind speeds and lake ice cover and temperature variables were detected using the sequential t-test STARS (Rodionov, 2004), which can automatically detect multiple change points.

## Results and Discussion

### *Shifts in air temperature and wind speed*

Annual air temperature (Fig. 2a) had a relatively small increase from 1910 until 1980, but has increased dramatically since 1981. Based on a piecewise linear regression algorithm, there was a

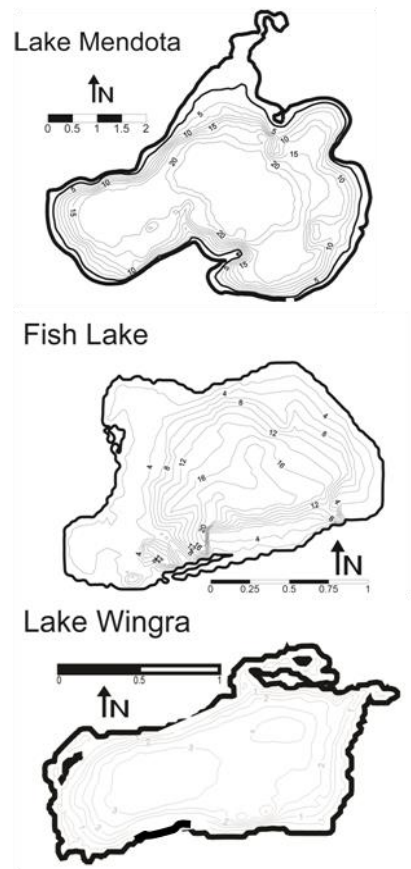


Figure 1: Bathymetric maps of Lake Mendota, Fish Lake, and Lake Wingra

small warming trend of  $0.081^{\circ}\text{C}$  per decade during 1911–1980, followed by a dramatic change (a warming trend of  $.334^{\circ}\text{C}$  per decade) from 1981–2014. Fig 2b shows that mean annual wind speed was  $4.44\text{ m s}^{-1}$  until 1994, when a significant shift occurred to  $3.74\text{ m s}^{-1}$  (15% reduction) based on the sequential t-test STARS method (Rodionov, 2004).

Combining the statistically significant breakpoint in air temperature trend that occurred in 1981 and the shift in wind speed in 1994, the Madison climate may be broken into three different periods. The first, from 1911–1980, was a relatively cool period and had an average wind speed of  $4.44\text{ m s}^{-1}$ . The second period (1981–1993) occurred after the breakpoint in the air temperature trend and had a warmer air temperature and a wind speed of  $4.44\text{ m s}^{-1}$ . The third period (1994–2014) occurred after the shift in wind speed from  $4.44\text{ m s}^{-1}$  to  $3.74\text{ m s}^{-1}$  and had even warmer air temperatures.

### ***Abrupt changes in lake variables***

To investigate the effects of abrupt changes in air temperature and wind speed on lake ice cover and water temperatures, we used the hydrodynamic model DYRESM-WQ-I to describe changes in several lake variables during 1911–2014. Simulation results were used to examine differences in mean values of these lake variables between specific periods. For each period of the selected periods, mean lake variables were calculated and the differences between periods were analysed with t-tests to determine if they were significantly different. Table 1 lists the mean values and differences for the nine lake variables during the three selected periods. Comparison of period 1 (1911–1980) to period 2 (1981–1993) of lake variables shows a shift to warmer air temperature; period 2 to period 3 (1994–2014) represents an abrupt change to lower wind speed; and period 1 to period 3 represents a shift to warmer air temperature combined with an abrupt change to lower wind speeds.

### ***Ice cover***

Three simulated ice cover variables (maximum ice thickness, ice-on date, and ice-off date) show no significant difference in means between period 1 and 2. In other words, the abrupt change in air temperature trend does not result in a different ice regime even though the ice cover variables are all highly correlated with air temperature ( $r > 0.70$ ). This may be because the change in air temperatures was not of sufficient magnitude to cause a particularly large change in ice cover or it may signify that other drivers are contributing to changes in ice cover variables. Additionally, no significant difference is observed between period 2 and period 3 for the ice cover variables since the wind speed and ice cover variables are only weakly correlated. The ice variables do show a statistically significant difference in mean values between periods 1 and 3, indicating that a significant shift in these variables occurs only after a sufficiently large increase in air temperature and an abrupt shift in

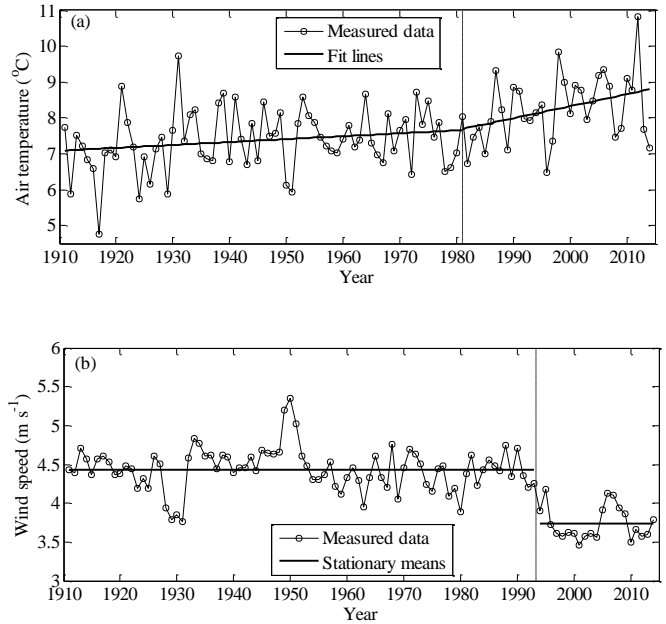


Figure 2: Historical record of annual average (a) air temperature and (b) wind speed in Madison, WI.

wind speed within the time between periods 1 and 3. In other words, air temperature need to increase sufficiently to observe a statistically significant difference in ice cover. Ice cover duration, however, shows a significant difference in the mean between all periods (1–2, 2–3, and 1–3), indicating that distinct differences in ice cover duration can be affected by both trends in air temperature (i.e., there was a large enough change in air temperature between each period) and an abrupt shift in the wind speed. The combined effects of slightly later ice-on dates and earlier ice-off dates during each of the three periods resulted in statistically significant difference in mean ice cover duration values between each of the three periods.

Table 1: Mean values of climate drivers and lake variables of three hypothesized periods during 1911–2014 for Lake Mendota. Asterisk (\*) mark significant differences between two periods ( $p < 0.05$ ).

		Period			Difference in Mean		
Driver/Variable	Unit	(1)1911-1980	(2)1981-1993	(3)1994-2014	(1) and (2)	(2) and (3)	(1) and (3)
Lake driver							
Air temperature (slope)	°C decade <sup>-1</sup>	0.081	0.334	0.334			
Wind speed	m s <sup>-1</sup>	4.44	4.44	3.74			
Lake variables							
Maximum ice thickness	cm	49.8	44.9	40.7	−4.9	−4.2	−9.1*
Ice-on date (model)	Date	21-Dec	23-Dec	29-Dec	2 days	6 days	8 days*
(observation)	Date	21-Dec	24-Dec	29-Dec	3 days	5 days	8 days*
Ice-off date (model)	Date	9-Apr	2-Apr	30-Mar	−7 days	−3 days	−10 days*
(observation)	Date	3-Apr	27-Mar	26-Mar	−7 days	−1 days	−8 days*
Ice duration (model)	Days	108.7	99.5	91.1	−9.2*	−8.4*	−17.6*
(observation)	Days	103.2	92.9	85.6	−10.3*	−7.3*	−17.6*
Under-ice water temperature	°C	1.74	1.81	2.08	0.07	0.27	0.34*
Freeze-over water temperature	°C	1.03	1.14	1.66	0.11	0.52	0.63*
Stratification onset date		24-May	17-May	18-May	−7 days	−1 days	−6 days
Mid-summer epilimnetic temperature	°C	23.0	23.2	23.4	0.2	0.2	0.4
Mid-summer hypolimnetic temperature	°C	12.0	11.8	10.9	−0.2	−0.9*	−1.1*
Epilimnion-hypolimnion temp. difference	°C	10.9	11.4	12.5	0.5	1.1	1.6*
Hypolimnetic heating (1 July–31 August)	°C	0.699	0.688	0.583	−0.011	−0.105	−0.116
Turnover date	Date	20-Sept	21-Sept	3-Oct	1 day	12 days*	13 days*
Stratification Duration	Days	119.4	127.4	138.6	8.0	11.2	19.2*

Analysis of simulated maximum ice thickness, ice-on, ice-off, and ice cover duration using the method of Rodionov (2004) shows that the most statistically significant timing of the shift in these ice cover variables occurs in the winter of 1997–1998, but a major shift in the air temperature or wind speed data was not observed at that time. The unusual winter of 1997–1998 strongly drove the statistically significant difference in mean values between periods 1 and 3 rather than the abrupt shift in wind speed in 1994. Interestingly, similar results have been reported in Lake Superior, where statistically significant step changes were found in winter ice duration and maximum wintertime ice extent; these step changes account for most of the long-term trends in ice cover for the lake (Van Cleave et al., 2014). The timing of this step change may be attributed to a combination of the longer term changes in meteorological conditions and the short-term annual change occurring in the warm El Niño winter of 1997–1998 (Van Cleave et al., 2014). Mueller et al. (2009) found that a similar climate shift between 1997 and 1998 initiated a change in lake ice phenology from infrequent to frequent summer loss in several high-Arctic lakes. Similarly, lakes in Poland show a considerable statistical relationship between ice cover and the North Atlantic Oscillation winter indexes (Skowron, 2009), indicating that ice cover may be driven by other large oscillations as well.

### *Water temperature and stratification*

Means of five simulated lake variables (under-ice water temperature, freeze-over water temperature, epilimnion-hypolimnion temperature difference [indicative of strength of stratification], and duration of stratification) over the three periods have significant ( $p < 0.05$ ) differences only between period 1 and period 3. This change likely occurs because of the combined effects of large changes in air temperature and a change in wind speed. Both air temperature and wind speed are significantly correlated with these five lake variables. Each driver alone may not be strong enough to cause a major shift in the lake variables, but their combined effects may reinforce the drivers of abrupt change in ice and thermal phenology. Further work is required to examine how the major drivers may either reinforce or dampen lake ice and temperature responses, particularly in relation to directional shifts predicted under climate change.

Fall turnover date, highly correlated with wind speed, exhibits a significant ( $p < 0.05$ ) shift in the mean value in 1994, corresponding with the abrupt shift in the wind speed. Interestingly, hypolimnetic water temperatures, which are not significantly correlated with wind speed, but are correlated with air temperatures, also show a significant ( $p < 0.05$ ) shift in the mean value in 1994. Hypolimnetic heating, significantly correlated with wind speed ( $r = 0.49$ ), does not exhibit a significant breakpoint, nor are any of the mean differences among the three periods significant. Given the high correlation between wind speed and hypolimnetic heating, it is hypothesized that there should be a shift in hypolimnetic heating caused by the abrupt shift in wind speed in 1994. The lack of statistically significant step change may be explained by the simultaneous high correlation between Secchi depth and hypolimnetic heating ( $r = 0.35$ ), indicating that water clarity may act to inhibit heating regardless of changes in wind speed, or it may be acting to filter or mitigate the effects of the wind speed shift. Finally, mean onset date of stratification and mid-summer epilimnetic temperature exhibit no difference among the three periods. This may be due to two processes: (i) the climate signal is being filtered out by the lake; or (ii) the external perturbation of the system is not yet strong enough to trigger a major shift in the system's internal dynamics.

### *Role of lake morphometry on response to historical climate changes*

#### *Temperature and stratification variables*

Pearson correlation coefficients in open water lake variables were calculated for pairs of study lakes (Table 2). Pair 1, Lake Mendota and Fish Lake, had similar depths but different surface areas, illustrating the effects of surface area differences. Pair 2, Lake Wingra and Fish Lake, had similar surface areas, but shallow and deep water depths, addressing the effects of lake depth. Pair 3, Lake Mendota and Lake Wingra, had both differing surface areas and water depths.

Epilimnetic temperature exhibited high coherence for all three pairs, suggesting that inter-annual variability in epilimnion water temperatures was primarily driven by climate drivers. Comparing the Mendota/Fish pair and the Fish/Wingra pair, the pair with similar surface area has higher correlation than the pair with similar depth. This suggests that both lake surface area and lake depth impact coherence between lake pairs; and surface area differences drive asynchronous patterns to a greater extent than does depth differences for epilimnetic temperature. Hypolimnion temperature, different from epilimnion temperature, showed only moderate coherence for the

Lake Variable	Lake Pair		
	Mendota/Fish	Wingra/Fish	Mendota/Wingra
Epilimnion Temperature	0.605	0.742	0.804
Hypolimnion Temperature	0.482	N/A	N/A
Stratification Onset	0.260	N/A	N/A
Fall Overturn	0.388	N/A	N/A
Schmidt Stability Number	0.761	0.405	0.346

Mendota/Fish pair, suggesting that inter-annual variability in hypolimnion water temperatures was driven by both climate drivers and other factors, such as lake morphometry. For example, differences in thermocline depth (~10 m in Lake Mendota and ~6 m in Fish Lake) can play a role in filtering the climate signals into the hypolimnion temperature. Other factors like strength of stratification and fetch differences may drive differences in the timing of stratification, further affecting hypolimnetic temperatures. Arvola et al. (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover. In our study, the relatively low hypolimnetic coherence for Lake Mendota and Fish Lake (Table 2) suggest that both climate drivers and lake morphometry play equally important roles in hypolimnion water temperatures. Coherence for stratification onset and fall overturn dates were low for the Mendota/Fish pair, suggesting that lake surface area may be a factor in driving differences between stratification onset and fall overturn in the lakes.

#### *Ice cover variables*

For the ice cover variables, correlation coefficients of pairs of lakes are high, e.g. ice on dates (Fish-Mendota:  $r = 0.99$ , Wingra-Fish:  $r = 0.99$ , Mendota-Wingra:  $r = 0.99$ ), ice-off dates (Fish-Mendota:  $r = 0.99$ , Wingra-Fish:  $r = 0.99$ , Mendota-Wingra:  $r = 0.99$ ), and maximum ice thickness Fish-Mendota:  $r = 0.98$ , Wingra-Fish:  $r = 0.93$ , Mendota-Wingra:  $r = 0.90$ ). The results suggest that morphometry does not play a significant role in the coherence of ice cover among the three study lakes. Similar results were reported in Alaska, where the average degree of coherence of ice-out within lake districts was 0.74 (Arp et al., 2013). The range of within-district coherence appeared similar among lakes within a district with varying elevations, lake size, and other morphometric and physiographic attributes (Arp et al., 2013), indicating that ice cover loss in lakes is driven primarily by air temperature. Nevertheless, previous studies showed the actual rate of decay and development of ice-free conditions do vary greatly from lake to lake within a region, depending on a number of factors, particularly lake morphometry and landscape setting (Brown and Duguay, 2010; Gao and Stefan, 1999; Williams et al., 2004).

### Effects of climate sensitivity on lake response

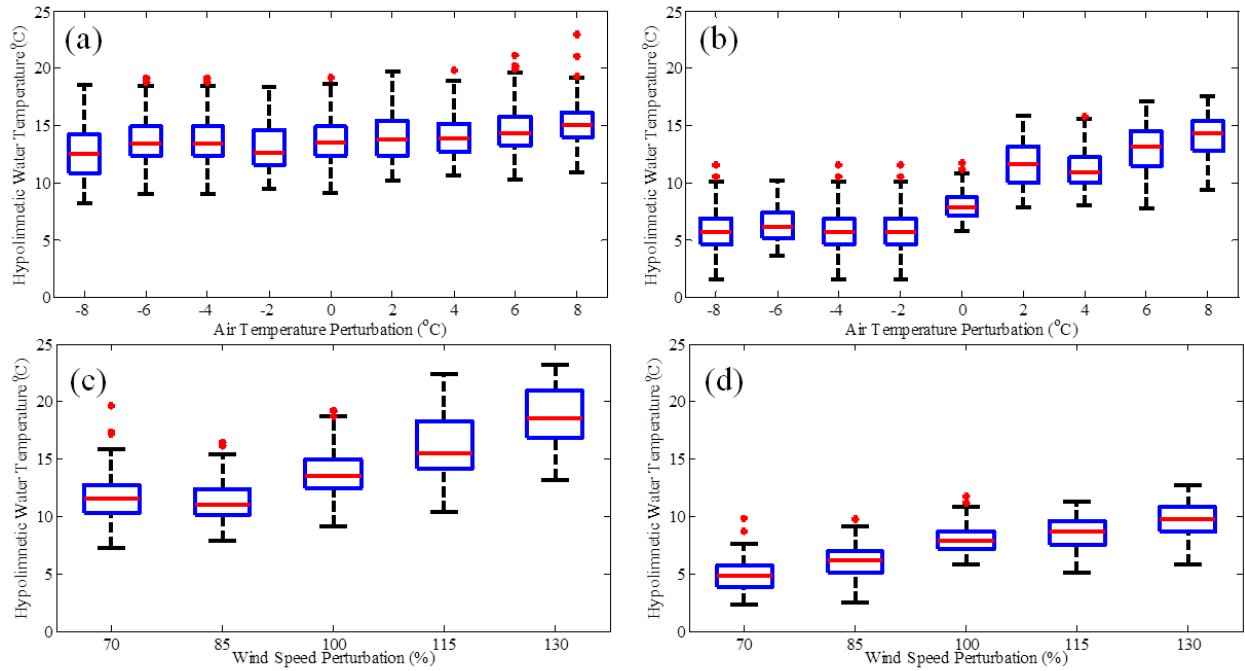
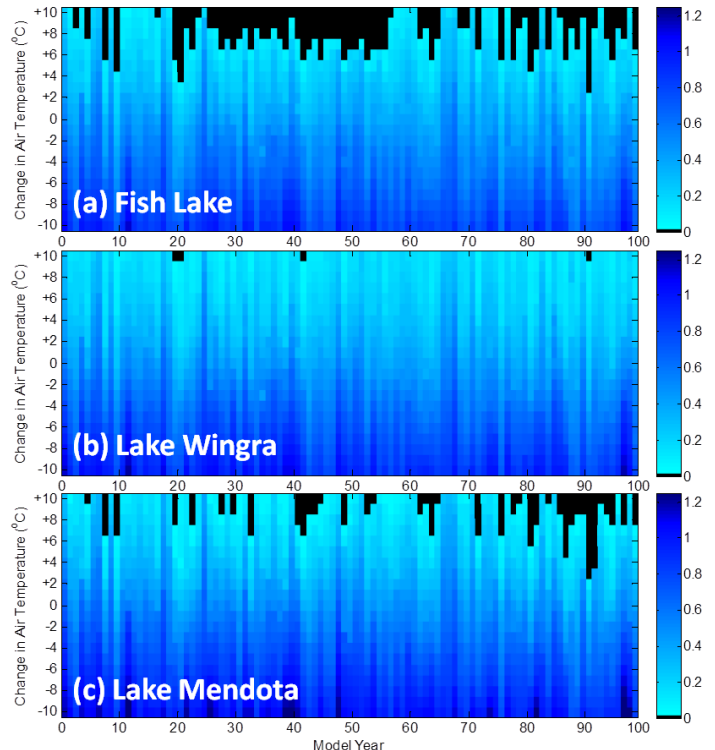


Figure 3: hypolimnetic water temperatures under select air temperature perturbations for (a) Lake Mendota and (b) Fish Lake and hypolimnetic water temperatures under select wind speed perturbations for (c) Lake Mendota and (d) Fish Lake.

For hypolimnetic water temperatures, changes with air temperature for both Lake Mendota and Fish Lake were linear, but changes under altered wind speeds were nonlinear. Temperature perturbations show increasing hypolimnetic water temperature for increasing air temperature, while decreasing wind speed perturbations show decreasing hypolimnetic water temperatures. Historically, hypolimnetic temperatures have been decreasing. Combining the effects of air temperature and wind speed, it appears that wind speed decreases are a larger driver of hypolimnetic water temperature changes than increasing air temperatures for both lakes. For example, in Lake Mendota, a 5% decrease in wind speed will offset the impacts to hypolimnetic temperature of a 1°C increase in air temperature, while in Fish Lake, a 12-13% decrease in wind speed is necessary to offset the effects of a 1°C increase in air temperature. This indicates that lakes with larger surface areas that also experience decreasing wind speeds may be more resilient



to increasing air temperatures increasing hypolimnetic water temperatures.

To examine sensitivity changes on ice cover (maximum ice thickness and ice cover duration) under cold or warm temperatures, we perform temperature perturbations by increasing and decreasing daily air temperature values for the first 100 years of the simulation period in 1°C intervals, bounded at -10°C and +10°C.

Figure 4 shows plots of maximum ice thickness with air temperature perturbations for 100 model years. Under the increasing air temperature, Fish Lake has the most occurrences of no ice cover (indicated by black color in Fig. 4). Lake Mendota has fewer ice-free occurrences because the larger lake surface area facilitates greater surface heat flux, which allows the lake to adjust to isothermal conditions and form ice more quickly. In contrast, almost all the ice cover remains in Lake Wingra as it has lower heat storages and responds more quickly to changes in air temperature. Overall, the results indicate that the deeper lakes are more at risk for thin or no ice conditions than shallow lakes. For cooler air temperatures (i.e. the bottom half of the colorplots), Fish Lake, Lake Wingra, and Lake Mendota all show similar increases in maximum ice thickness.

## Conclusions and Recommendations

Changes in meteorological factors over the past 104 years were examined on Lake Mendota to determine if there have been abrupt shifts, rather than linear changes.

Based on a change in the trend of air temperature increase occurring in 1981 and a major shift in wind speed in 1994, the Madison climate is divided into three distinct periods: 1911–1980, with relatively low air temperatures and mean wind speeds of 4.44 m s<sup>-1</sup>; 1981–1993, with higher air temperatures and mean wind speeds of 4.44 m s<sup>-1</sup>; and 1994–2014 with still higher air temperatures and mean wind speed of 3.74 m s<sup>-1</sup>. Ice cover duration exhibited a significant difference in the mean among all three periods, while ice-on, ice-off, and maximum ice thickness only show a significant difference between period one and three, indicating that only with a large change in air temperature and an abrupt shift in wind speeds are change in the ice cover variables statistically different. Mid-summer hypolimnetic temperature and fall turnover date both reveal significant ( $p < 0.05$ ) differences in the mean value in 1994, corresponding with the abrupt shift toward lower wind speeds. Some lake variables (under-ice water temperature, freeze-over water temperature, epilimnion-hypolimnion temperature difference, and stratification duration) may not be driven by either the change in air temperature trend or the abrupt shift in wind speed alone, but a shift in the mean of the lake variables does occur in 1994 when both the air temperatures are warmest and the wind speed experienced an abrupt shift. The exact timing of shifts may be difficult to define because of extreme changes in weather in specific years and it may mask the longer term changes in meteorological conditions (i.e. abrupt shifts).

Analysis of ice cover on three different study lakes indicates that shallow lakes, such as Lake Wingra, are more resilient to changes in air temperature than their deeper counterparts. Even under extreme increases in air temperature, model results indicate that Lake Wingra will still have ice cover, whereas the deeper Fish Lake and Lake Mendota will not. Since the shallow depth in Lake Wingra facilitates heat loss more quickly during the winter, causing ideal conditions for ice cover even under extreme warm air temperatures. Additionally, lakes with large surface areas can cool more quickly through wind mixing, which allows for easier ice formation on those lakes compared to lakes of similar depth with smaller surface areas. Overall, shallow lakes with large surface areas are

Figure 4: Maximum ice thickness (in m) for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota for air temperatures ranging from -10 to +10 °C perturbations of historical temperatures

most resilient to ice cover changes caused by climate and deep lakes with small surface areas are the least resilient to climate-induced ice cover changes

Previous research has shown uncertainty in the changes in hypolimnion water temperatures for dimictic lakes, however the perturbation scenarios indicate that while increasing air temperature always increases hypolimnion temperature, wind speed is a larger driving force, and the ultimate hypolimnion temperature response will be determined by whether the lake experiences an increase or decrease in wind speeds. Overall, lake depth and lake surface area impact the changing thermal structure in response to climate change. Fish Lake has a much earlier average stratification onset and later fall overturn because of its smaller surface area and less wind-mixing, and the effects of the changing trend is more immediate due to the already long stratified period. A larger magnitude of trend for these changes is shown in Lake Mendota, indicating that larger and deeper lakes are more susceptible to changing climate. Lake Mendota experienced greater variability in stability between high and low air temperature and high and low wind speed years than Fish Lake, suggesting that stability in the larger surface area is more susceptible to changes in the climate variables than in the lake with smaller surface area.

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## Appendix A

### Publications:

Magee, M. R., Wu, C. H., Robertson, D. M., Lathrop, R. C., and Hamilton, D. P.. 2016. Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers, *Hydrol. Earth Syst. Sci. Discuss.*, doi:10.5194/hess-2015-488.

Magee, M.R. and Wu, C.H. Effects of changing climate on ice cover in three morphometrically different lakes. *Accepted under revision to Hydrological Processes*

Magee, M.R. and Wu, C.H. Response of water temperature and stratification to changing climate in three lakes with different morphometry. *Submitted to International Journal of Limnology*

### Presentations:

Magee, M.R. and Wu, C.H. (March 2016). *Fish kills and oxythermal stress under climate and land use changes*. Wisconsin Ecology Symposium, Madison, WI, Poster Presentation. 60 attendees.

Magee, M.R. and Wu, C.H. (March 2016). *Fish kills and oxythermal stress under climate and land use changes*. American Water Resources Association-Wisconsin Section, Wisconsin Dells, WI, Poster Presentation. 50 attendees.

Magee, M.R. (February 2016). *Impact of climate change on ice cover and thermal structure in response to changing climate*. Environmental Engineering seminar. Madison, WI, Oral presentation. 25 attendees.

Magee, M.R. and Wu, C.H. (March 2015). *Temperature Dosage: A Novel Method for Quantifying Oxythermal Stress in Coldwater Fish Species*. American Water Resources Association-Wisconsin Section, Oconomowoc, WI, Poster Presentation. 50 attendees.

Magee, M.R. (April 2013). *Oxythermal Stress of Cisco in Fish Lake in Response to Changing Climate*. North Temperate Lakes LTER Young Scientist Meeting, 30 attendees

Magee, M.R. and Wu, C.H. (March 2013). *Oxythermal Stress of a Dimictic Lake in Response to Changing Climate*. American Water Resources Association-Wisconsin Section. Brookfield, WI. Oral Presentation. 25 attendees

Gerdts, N. and Wu, C.H. (March 2013) *Seasonal evaporation of two different morphometry lakes under changing climate*. American Water Resources Association-Wisconsin Section. Brookfield, WI. Oral Presentation. 30 attendees

Magee, M.R. and Wu, C.H. (November 2012). *Impacts of Climate Change on Ice Cover and Thermal Structure in Southern Wisconsin Lakes of Differing Morphometry*. 32nd International Symposium of the North American Lake Management Society. Madison, WI. Oral Presentation 40 attendees

Magee, M.R. and Wu, C.H. (March 2012). *Impacts of Climate Change on Ice Cover and Thermal Structure in Three Southern Wisconsin Lakes of Differing Morphometry*. American Water Resources Association-Wisconsin Section. Wisconsin Dells, WI. Oral Presentation. 30 attendees

Magee, M.R. (November 2011). *Impact of Climate Change on Ice Cover in Three Southern Wisconsin Lakes with Differing Morphometry*. North Temperature Lakes LTER Young Scientist Meeting, 25 attendees

Magee, M.R. and Wu, C.H. (September 2011). *Trends of Ice Cover and Thermal Structure of Three Southern Wisconsin Lakes*. National Science Foundation, LTER-NTL Site Review. Trout Lake Station, WI. Poster Presentation. 30 attendees

### **Students:**

First Name: Madeline  
Last Name: Magee  
Campus: University of Wisconsin-Madison  
Advisor First Name: Chin  
Advisor Last Name: Wu  
Advisor Campus: University of Wisconsin-Madison  
Degree/Training (*Masters, PhD, Post-Doc, Expected Masters, Expected PhD, Expected Other, Undergraduate, Other*): Expected PhD  
Graduation Month: December  
Graduation Year: 2016  
Department: Department of Civil and Environmental Engineering  
Contact: mrmagee@wisc.edu

First Name: Nathan  
Last Name: Gerdts  
Campus: University of Wisconsin-Madison  
Advisor First Name: Chin  
Advisor Last Name: Wu  
Advisor Campus: University of Wisconsin-Madison  
Degree/Training (*Masters, PhD, Post-Doc, Expected Masters, Expected PhD, Expected Other, Undergraduate, Other*): Masters  
Graduation Month: May  
Graduation Year: 2015  
Department: Department of Civil and Environmental Engineering  
Contact: [ngerdts@wisc.edu](mailto:ngerdts@wisc.edu)

### **Impact:**

Results of the investigation of the impact of changing climate to Wisconsin lakes provides quality information to lake managers and other researchers. Understanding the change of water temperature may allow regulatory agencies to determine which lakes may become at risk for invasive species. This allows agencies to direct their manpower to a few specific lakes to prevent

species spread rather than having to monitor a variety of lakes, some of which may not be at risk to invasive species. Additionally, as water temperature greatly affects fish species within the lakes, understanding which lakes may be at risk for fish kills due to increasing stratified period or increasing water temperatures may allow for mitigation efforts to protect important fish populations.

# Establishing the Long-Term Range of Variability in Drought Conditions for Southwest Wisconsin

## Basic Information

<b>Title:</b>	Establishing the Long-Term Range of Variability in Drought Conditions for Southwest Wisconsin
<b>Project Number:</b>	2013WI313B
<b>Start Date:</b>	3/1/2014
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	3rd
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Drought, Models, Management and Planning
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Evan Reed Larson, Christopher Underwood

## Publication

1. Allen, S. and Larson, E.R. 2014. The Driftless Oaks: An environmental history of southwest Wisconsin. Wisconsin Natural Resources 38: 6-7. [available: <http://dnr.wi.gov/wnrmag/2014/10/Oak.htm>]

# Second Annual Report for Driftless Oaks project

Reporting Period: 3/1/2015 - 2/29/2016

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## Project

WR13R003 - Establishing the long-term range of variability in drought conditions for Southwest Wisconsin

## Principle Findings and Significance

Field work for this project spanned two years and resulted in tree-ring samples collected from a total of 368 living trees, 15 stumps, and 17 beams from six historic structures at 46 sites across southwestern Wisconsin during the winters of 2012–13 and 2013–14. Crossdating was successful on 731 core samples and cross sections that resulted in the development of 46 site-level tree-ring chronologies. These were combined into a regional chronology that spanned 1677–2014 and exhibited a strong and consistent relationship with summer drought. The reconstruction produced from this regional chronology illustrated that the drought frequency changed over time, with the 1700s and 1900s being relatively wet compared to the drought-stricken 1800s. The past 100 years represent the wettest period in three centuries. A substantial drought persisted across the study area for nearly 40 years in the mid-1800s that is of an extent not observed over the instrumental period. The driest year in the last three centuries is 1895, and years of equal or more intense drought relative to the summer of 2012 have occurred every few decades. The regional tree-ring chronology we developed is significantly correlated with standardized annual yields per acre of corn ( $r = 0.38$ ,  $n = 87$ ,  $p = 0.0001$ ) and soybeans ( $r = 0.30$ ,  $n = 77$ ,  $p = 0.004$ ) in Grant County of Southwest Wisconsin, highlighting the potential usefulness of tree-rings as a proxy for understanding the changing growing conditions in southwest Wisconsin. In addition to producing a robust climate reconstruction that improves our understanding of water resource availability in southwest Wisconsin, over 30 undergraduate students participated in this research, including multiple students who took on certain aspects of the project through independent study. Five of these students were able to attend a conference to share their research findings. We also hosted a thank you event for all of the landowners who contributed to the project, during which we presented our results to disseminate the research and to promote the idea of teaching through mentored research.

Progress from March 1, 2015 through February 29, 2016, included a more thorough statistical vetting of the climate-growth relationships discussed in the previous Annual Report, five invited presentations to academic and community organizations, and the identification of a significant

## Number of Personnel Involved

2 Participating faculty/staff

0 Supported post-docs

## Students Supported

No students reported.

Conference Participation

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**Title**  
Department of Geography Colloquium

**Location**  
Northern Illinois University, DeKalb, Illinois

**Dates**  
March 6, 2015

**Presentations by Staff**  
The Good Oak: Stories of Midwestern drought and hydrologic change through tree rings, presented by Evan Larson

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**Title**  
Ox-Bow School of Art Visiting Faculty Seminar Series

**Location**  
Art Institute of Chicago Ox-Bow Campus, Saugatuck, Michigan

**Dates**  
August 13, 2015

**Presentations by Staff**  
The environmental history at Ox-Bow, presented by Evan Larson and J. Elmo Rawling III

---

**Title**  
Ralph Nuzum Lecture Series

**Location**  
Kickapoo Valley Reserve, La Farge, Wisconsin

**Dates**  
June 25, 2015

**Presentations by Staff**  
The profound impacts of invasive earthworms on hardwood forests in Wisconsin, presented by Evan Larson (the Driftless Oaks project was the focus of the first 15 minutes of this hour-long seminar)

---

**Title**  
UW-Platteville Tree-Ring, Earth, and Environmental Sciences Laboratory (TREES Lab) Lecture

**Location**  
TREES Lab, Platteville, Wisconsin

**Dates**  
May 5, 2015

**Presentations by Staff**  
The Driftless Oaks Project: A reception for landowners, presented by Evan Larson and Sara Allen; this presentation was given in coordination with a tour of the TREES Lab and dinner provided in thanks to the landowners who

participated in the project by allowing us to sample trees on their property.

### **Journal Articles and Other Publications**

No journal articles and other publications reported.

### **Awards and Achievements**

No awards and achievements reported.

### **Research Patent or Copyright**

No research patents or copyrights reported.

### **Completion Summary**

Conclusions/Implications/Recommendations: The primary finding from this research is that drought conditions in Southwest Wisconsin have varied widely in the past and we should expect them to continue to do so into the future. This is particularly important because despite the constantly increasing yield per acre for corn and soybeans, recent research suggests that modern agriculture is more sensitive to climate variations because we are pushing production to the maximum amount possible. Perhaps it is time to discuss approaches to buffering agricultural systems so that if climate continues to become increasingly variable and severe, as is predicted under changing climate conditions, the people who rely on water and agriculture are well prepared for whatever conditions that may occur.

Opportunities exist to further improve the data collected for this project. In particular, early exploratory work suggests that old red cedar persist on the bluffs and outcrops of the Driftless Area that could further extend our reconstruction into the past while offering additional opportunities for UW-Platteville student researchers.

**ESTABLISHING THE LONG-TERM RANGE OF VARIABILITY IN DROUGHT CONDITIONS FOR  
SOUTHWEST WISCONSIN**

Project I.D.: WR13R003

*Investigators:*

Evan R. Larson  
Associate Professor  
Department of Geography  
University of Wisconsin-Platteville

Sara A. Allen  
Research Specialist  
Tree-Ring, Earth, and Environmental Sciences Laboratory (TREES Lab)  
Department of Geography  
University of Wisconsin-Platteville

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## PROJECT SUMMARY

**Title:** Establishing the long-term range of variability in drought conditions for southwest Wisconsin

**Project I.D.:** WR13R003

**Investigators:** **Evan R. Larson**

Associate Professor  
Department of Geography  
University of Wisconsin-Platteville

Sara A. Allen  
Research Specialist  
Tree-Ring, Earth, and Environmental Sciences Laboratory (TREES Lab)  
Department of Geography  
University of Wisconsin-Platteville

**Period of Contract:** March 1, 2013–December 31, 2015

**Background and Need:** Establishing the range of variability in water resources over recent centuries is critical for effectively managing existing water resources, understanding trends in water availability, and planning for future conditions. In particular, the economic wellbeing of the agricultural communities of southwest Wisconsin are strongly influenced by extremes in water availability, as illustrated by the extreme rainfalls and flooding of 2008 and the drought of 2012. Long-term records of drought can help plan for future conditions.

**Objectives:** The purpose of this project was to locate old-growth oak trees growing across southwest Wisconsin, collect tree-ring samples from them, and use regionally-coherent patterns of ring width variability to infer hydrologic conditions for the Driftless Area of southwest Wisconsin over recent centuries. In addition to the scientific objective of this research, a broader objective was to utilize this research as a high-impact educational tool to engage undergraduate students in authentic research experiences in field and laboratory settings.

**Methods:** Field work for this project included numerous scouting and sampling trips within the 10 counties that compose the Driftless Area of southwest Wisconsin. This area supported extensive tracts of oak savanna habitat at the time of European settlement and we therefore targeted it in search of pre-settlement oaks that remain on the landscape. After exhausting all available public land, we conducted outreach to private landowners through a short story on Wisconsin Public Radio and an article in the Wisconsin Natural Resources magazine. These efforts yielded invitations from over 250 landowners to consider including trees on their property in the study. Once the potential sites were honed down through phone conversations and site visits, we used Swedish-made increment borers to collect tree core samples from the oldest trees found at each site. The core samples were dried, mounted into wooden core trays for structural stability, and sanded to a high polish. The annual growth rings of each sample were assigned exact calendar dates and measured using specialized tree-ring analysis software. Patterns of ring-width were composited within sites and across the study area to capture a regional climate signal embedded in the growth patterns of the sampled trees. Climate-tree growth relationships were determined through correlation analysis with climate data collected at stations across the study area, and a regression was developed to estimate past summer (June–July–August) drought conditions over the full extent of the tree-ring record. The reconstruction was interpreted to describe the frequency, duration, and intensity of

droughts in the past, and compared to crop yield data for Grant County to determine if insight from tree-rings can be useful to farmers and others in agriculture.

**Results and Discussion:** Field work for this project spanned two years and resulted in tree-ring samples collected from a total of 368 living trees, 15 stumps, and 17 beams from six historic structures at 46 sites across southwestern Wisconsin during the winters of 2012–13 and 2013–14. Crossdating was successful on 731 core samples and cross sections that resulted in the development of 46 site-level tree-ring chronologies. These were combined into a regional chronology that spanned 1677–2014 and exhibited a strong and consistent relationship with summer drought. The reconstruction produced from this regional chronology illustrated that the drought frequency changed over time, with the 1700s and 1900s being relatively wet compared to the drought-stricken 1800s. The past 100 years represent the wettest period in three centuries. A substantial drought persisted across the study area for nearly 60 years in the mid-1800s that is of an extent not observed over the instrumental period. The driest year in the last three centuries is 1895, and years of equal or more intense drought relative to the summer of 2012 have occurred every few decades. The regional tree-ring chronology we developed is significantly correlated with corn and soybean yield for Grant County, highlighting the potential usefulness of tree-rings as a proxy for understanding the changing growing conditions in southwest Wisconsin.

In addition to producing a robust climate reconstruction that improves our understanding of water resource availability in southwest Wisconsin, over 30 undergraduate students participated in this research, including multiple students who took on certain aspects of the project through independent study. Five of these students were able to attend a conference to share their research findings. We also hosted a thank you event for all of the landowners who contributed to the project, during which we presented our results to disseminate the research and to promote the idea of teaching through mentored research.

**Conclusions/Implications/Recommendations:** The primary finding from this research is that drought conditions in Southwest Wisconsin have varied widely in the past and we should expect them to continue to do so into the future. This is particularly important because despite the constantly increasing yield per acre for corn and soybeans, recent research suggests that modern agriculture is more sensitive to climate variations because we are pushing production to the maximum amount possible. Perhaps it is time to discuss approaches to buffering agricultural systems so that if climate continues to become increasingly variable and severe, as is predicted under changing climate conditions, the people who rely on water and agriculture are well prepared for whatever conditions that may occur.

Opportunities exist to further improve the data collected for this project. In particular, early exploratory work suggests that old red cedar persist on the bluffs and outcrops of the Driftless Area that could further extend our reconstruction into the past while offering additional opportunities for UW-Platteville student researchers.

**Key words:** Drought, tree rings, dendrochronology, oak trees, Driftless Area, agriculture

**Funding:** This research was supported by funding through the University of Wisconsin Water Resources Institute, the University of Wisconsin-Platteville College of Liberal Arts and Education, and the UW-Platteville Tree-Ring, Earth, and Environmental Sciences Laboratory (TREES Lab).

## INTRODUCTION

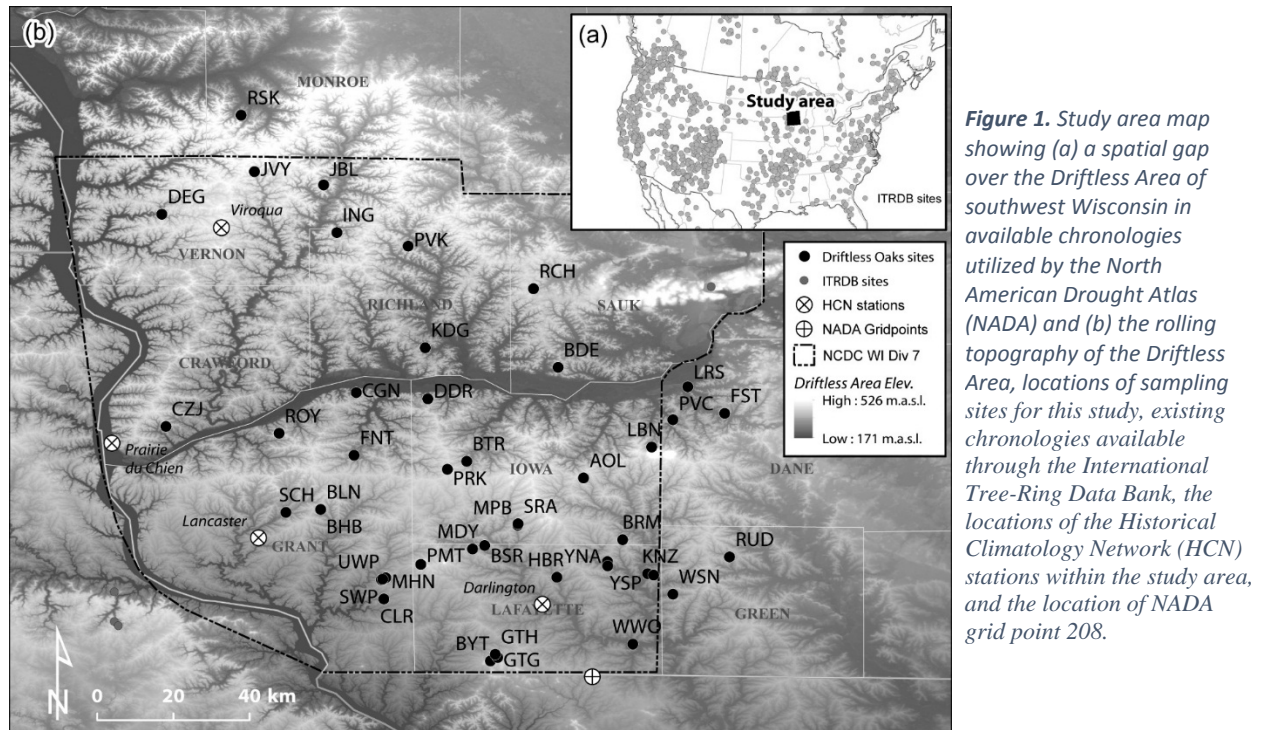
Tree-ring based reconstructions of climate offer key insights for understanding climate variability over long time periods and can provide context for recent climate extremes in order to better understand how climate is changing and to prepare for future conditions. This is particularly valuable for agricultural regions of the world where the availability of water can determine the success or failure of crops, economies, and societies (Douglass 1929, Weiss *et al.* 1993, Acuna-Soto *et al.* 2005, Cook *et al.* 2007, Buckley *et al.* 2010, Cook *et al.* 2010). The upper Midwest of the United States is an agricultural region with a low density of tree-ring chronologies relative to elsewhere in North America. The sparse availability of tree-ring data is in part due to diminishing tree cover across the biogeographic transition to prairie traveling east to west, as well as the widespread logging that occurred in the 1800s and 1900s that removed much of the primary forest that once covered the region (Rhemtulla *et al.* 2007). Opportunities to locate and sample old trees remain, however, particularly in ecological settings where the dominant trees of the pre-European landscape were relatively long-lived such as in the oak savannas that were found in the region along the prairie-forest ecotone (Nuzzo 1986). Researchers have utilized the growth rings of old oak trees in Iowa, Illinois, and Missouri to develop hydrologic reconstructions (Duvick and Blasing 1981, Blasing and Duvick 1984, Cleveland and Duvick 1992, Stambaugh *et al.* 2011), yet a substantial area of what once was oak savanna at the time of European settlement remains without tree-ring data. At the same time, a long-term perspective on drought would greatly benefit this region where recent extreme events, such as the extreme drought of 2012, highlighted the susceptibility of the region's agricultural systems to drought (Boyer *et al.* 2013).

Here, we report the development of a new set of multi-century tree-ring chronologies from oak trees growing across the Driftless Area of southwestern Wisconsin, USA, that fill a spatial gap in the network of currently available tree-ring chronologies (Figure 1a). We use this new set of chronologies to reconstruction patterns of drought over recent centuries and to quantify variability in the frequency, duration, and intensity of drought across the Driftless Area.

## PROCEDURES AND METHODS

### Study Site Description

The Driftless Area is a rural landscape of rolling hills dissected by steep stream valleys located in the Upper Midwest of the United States (Figure 1b) (Martin 1965). Named for its lack of glacial deposits, the Driftless Area was surrounded, but never over run, by Pleistocene glaciers, resulting in geographically-distinct terrain relative to the glaciated regions of central and northern North America (Attig *et al.* 2011). Relief across the Driftless Area is dramatic for the Upper Midwest, with numerous ridges and bluffs rising 100 or more meters above neighboring flood plains. Bedrock throughout the Driftless Area is sedimentary, with limestone and sandstone the primary rock types. Karst topography and caves are common, as are sandstone bluffs and outcrops on ridges between stream channels. A thick mantle of loess was deposited across the area during glacial and interglacial periods. The soils of the Driftless Area are nutrient rich with excellent water holding capacity and therefore highly valued for agriculture. The primary crops of the region are corn and soybeans, with extensive pastures for dairy and cattle grazing. The complex topography of the Driftless Area has generally limited the size of farms and fields in most places and irrigation systems rare, making the region susceptible to extreme events.



**Figure 1.** Study area map showing (a) a spatial gap over the Driftless Area of southwest Wisconsin in available chronologies utilized by the North American Drought Atlas (NADA) and (b) the rolling topography of the Driftless Area, locations of sampling sites for this study, existing chronologies available through the International Tree-Ring Data Bank, the locations of the Historical Climatology Network (HCN) stations within the study area, and the location of NADA grid point 208.

The land cover of the Driftless Area is a pastoral mix of agriculture and woodlands. Crop lands are primarily found on flood plains and where ridge tops are sufficiently broad and level, while extensive pastures cover more rolling terrain. Steeper hill sides are generally forested by a mix of hardwood species including oak (*Quercus* spp.), hickory (*Carya* spp.), maple (*Acer* spp.), and basswood (*Tilia americana*) (Curtis 1959). The modern landscape is markedly different than that encountered by European settlers moving into the area in the early 1800s. At that time the Driftless Area was situated along the prairie-forest border and was largely covered by tallgrass prairie and oak savanna, with maple-basswood forests on wetter sites (Davis 1977). Records from the U.S. General Land Office Public Land Surveys describe widespread savannas populated by bur oak (*Quercus macrocarpa*) and white oak (*Quercus alba*) trees (Finley 1976). Both of these oak species have thick bark and are drought tolerant, enabling them to withstand the frequent surface fires and occasional droughts that maintained open grasslands throughout the area. The longevity of these species, with maximum life spans extending multiple centuries, coupled with the success of interpreting the growth rings of oaks in this and other regions as reliable recorders of drought conditions (e.g., Cleveland and Duvick 1992, Drobyshev *et al.* 2011, Stahle *et al.* 2013, Gildehaus *et al.* 2015), led us to focus on identifying presettlement oak trees across southwestern Wisconsin to develop multi-century proxy records with the intent of reconstructing drought.

### Tree selection and field methods

The identification of sampling locations across the Driftless Area was a distinct challenge for this research. Reconstructing regional climate using tree rings requires that the trees sampled are distributed across the region of interest and that sampling efforts are targeted to control for differences in topographic and microsite settings to maximize the climate signal of interest. Furthermore, the funding we received for this research was specifically linked to research within the state of Wisconsin. We therefore focused on the portion of the Driftless Area in southwestern Wisconsin, yet the majority of land in this area is divided into small, private holdings. Our sampling efforts therefore took two approaches to identify

suitable sampling sites. First, land managers were consulted and almost all public land in southwest Wisconsin was considered, with those sites that likely supported oak savanna habitat in the early 1900s being surveyed on foot for potentially old trees. These efforts were complemented by a public outreach effort that included a short story on Wisconsin Public Radio (Quirnbach 2013) and an article in Wisconsin Natural Resources Magazine, a publication produced by the Wisconsin Department of Natural Resources (Allen and Larson 2014). Together, these efforts resulted in over 250 invitations to scout private lands for potential inclusion in the project.

Old living oak trees at each site were identified through surveys and with the help of numerous landowners. Two considerations were emphasized in locating living bur oak and white oak trees to sample: 1) spreading crown structures that suggested the trees established and grew in open conditions with the intent to minimize the influence of inter-tree competition on tree growth patterns, and 2) trees growing on warmer and drier south and southwest-facing ridges, bluff edges, or steep topography to maximize the likelihood of ring-width being limited by moisture availability. Each sampled tree was inventoried for species, crown structure, health, and diameter at breast height (DBH), photographed, and georeferenced. We attempted to obtain increment cores along at least two radii per tree, though in some cases rot was a limiting factor. Throughout this process we worked with landowners to communicate the scientific value these trees represent while consistently being impressed by the pride and appreciation people felt for their oak trees. In addition to sampling living trees, we collected tree-ring samples from *in situ* oak stumps and historic structures that contained oak beams that were likely of local origin. A chainsaw was used to collect cross sections from stumps, while an archaeological bit was used to collect 15 mm diameter core samples from historic structures at locations along each sampled beam that likely included cambium. Field work was conducted primarily by teams of undergraduate students led by the authors. All living trees were sampled during the dormant season (October–April) to minimize risk of oak wilt affecting the sampled trees.

### **Chronology development**

Teams of undergraduate students, under mentorship from the authors, developed ring-width chronologies for most sites, with the authors developing the balance and conducting quality checks on all project data. All tree-ring samples were air-dried. Core samples were glued to wooden increment core trays and cross sections were glued to plywood. Each sample was surfaced by progressively sanding from relatively coarse (ANSI 60–80 grit) to fine (ANSI 400–600 grit) abrasive paper until a polished surface was obtained (Stokes and Smiley 1996). Master chronologies were developed for each site by visual crossdating and skeleton plotting (Yamaguchi 1990, Stokes and Smiley 1996). Tree-ring samples from stumps and structures were crossdated with nearby site chronologies from living trees. All crossdated samples were scanned at 1200+ dpi resolution using a flatbed scanner and ring-width measurements were collected using WinDENRO v2012 (Regent Instruments, Inc.). Crossdating of each ring-width series was confirmed using the computer software COFECHA (Holmes 1999, Grissino-Mayer 2001).

Standardized ring-width index (RWI) chronologies were developed for each site individually and for the study area as a whole. Visual inspection of the individual tree-ring samples found that the vast majority exhibited wide inner rings indicative of open-grown trees (Fritts 1976). The age-related growth trend of each series was therefore removed by dividing each ring-width measurement by a value drawn from a linear regression with negative slope, a negative exponential curve, or a horizontal line through the mean that was fit to each measurement series. Residual (RES) chronologies were developed by combining the unitless indices for each year of the chronology using a robust bi-weight mean that minimized the influence of outliers, then removing all autocorrelation from the RWI chronology through autoregressive modeling (Cook 1985). The RES chronologies therefore represented only the year-to-year variations in

growth at each of the sites. Autoregressive standardized (ARSTAN) chronologies were developed for each site by identifying and retaining the shared autocorrelation among RWI series that likely represented persistence in the climate system (Cook 1985). The ARSTAN chronologies therefore retained interannual- to decadal-scale low-frequency variability that could relate to longer-term fluctuations in climate conditions (Cook 1985). The RES and ARSTAN chronology development was carried out using the computer program Arstan v44h2 (Cook and Krusic 2013).

We developed a regional RWI chronology based on the entire set of ring-width measurements considered as a whole. The relatively high number of tree-ring samples collected with respect to the extent of our study area improved the likelihood of statistically identifying the common growth signal among the samples that was related to climate (*sensu* Büntgen *et al.* 2012). Signal-free standardization is a recently developed technique meant to retain low-frequency variability while reducing the trend distortion that is a common result of other approaches to standardization (Melvin and Briffa 2008). A regional signal-free (SSF) chronology was developed by iteratively identifying and removing the common forcing signal from each measurement series using relatively stiff 100-yr splines. Repeated applications of the process eventually produced little meaningful difference in the resulting chronology based on median absolute differences, a condition described as convergence. Upon convergence, the residual “signal-free” curve for each measurement series was used to standardize each time series as the ratio of actual to expected growth. The resulting indices were combined into a chronology using a biweight robust mean. Signal-free standardization was conducted using the computer program RCSsigFree v45 (Cook *et al.* 2014).

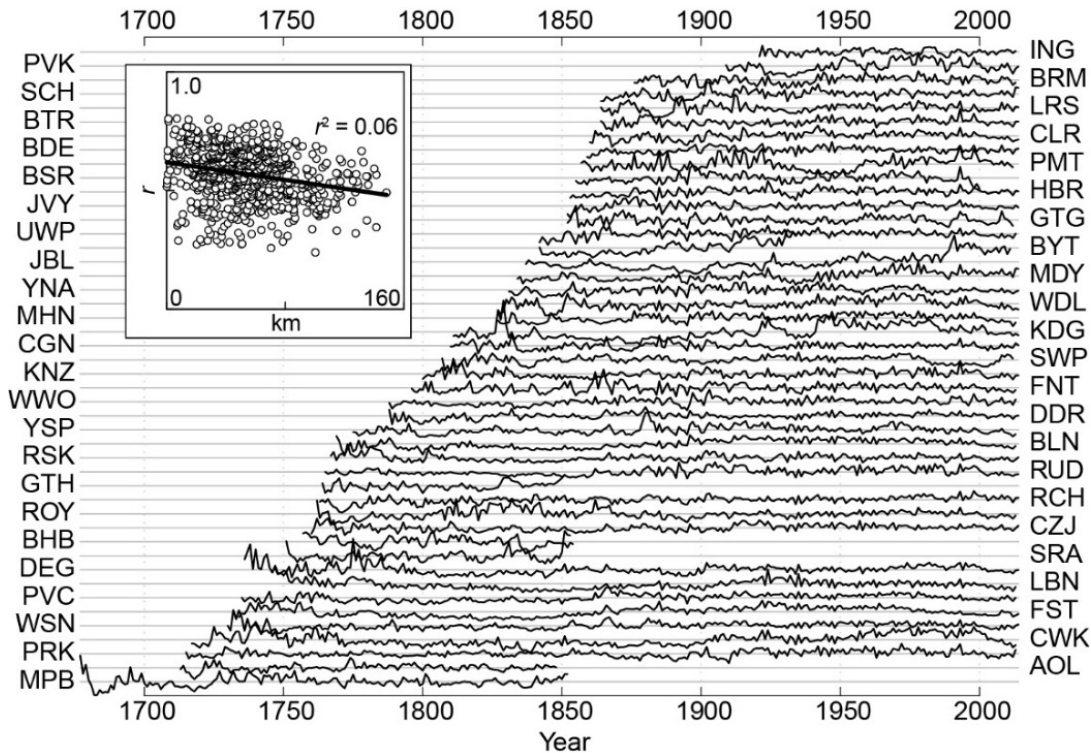
### **Calibration, Verification, and Reconstruction**

Each site chronology was compared to monthly records of precipitation, mean temperature, maximum temperature, minimum temperature, and Palmer’s Drought Severity Index (PDSI, Palmer 1965) for NCDC Wisconsin Climate Division 7 using correlation analysis in order to obtain a general understanding of climate-tree growth relationships across our study area. Exploratory analyses indicated that tree-growth was more strongly related to seasonal climate than individual months. We therefore focused our analyses on three seasonalized climate variables: April–June precipitation, June–July maximum temperatures, and June–August PDSI. All RES and ARSTAN individual site chronologies were correlated with the seasonalized climate variables over the time period 1895–2014 to examine long-term climate-growth relationships among the sites. The temporal stability of the site-scale climate-growth relationship was examined using moving 40-yr correlations with each of the seasonalized climate variables. The climate variable exhibiting the strongest and most consistent relationship with the site chronologies and that was most reasonably explained by our sampling sites and tree physiology was chosen as a target for reconstruction.

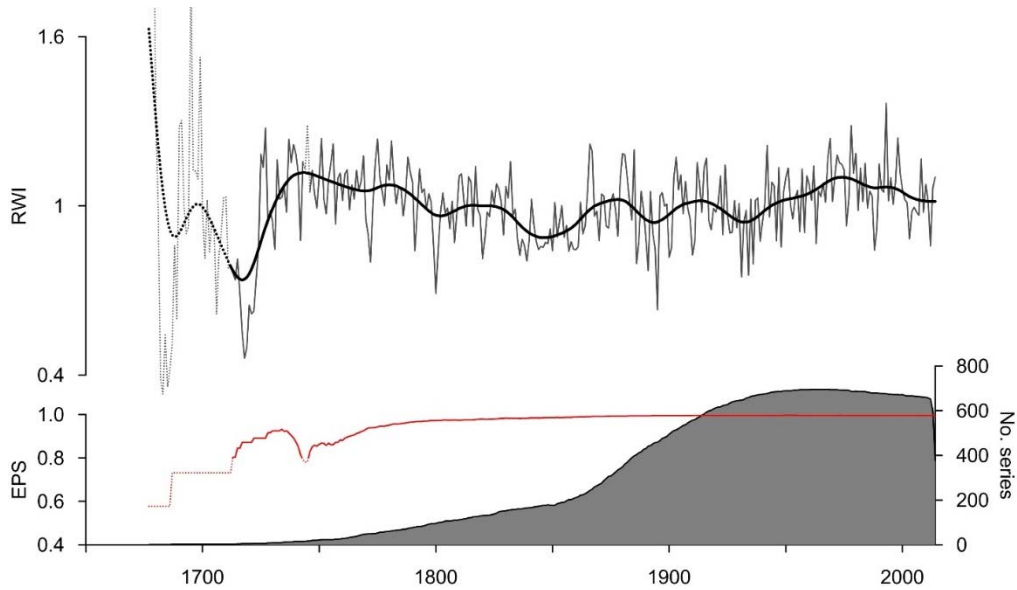
A reconstruction was developed by comparing the regional SSF chronology with the monthly and seasonal divisional precipitation, maximum temperature, and PDSI data using response function analysis, correlation analysis, and moving correlation analysis over 40-yr windows as implemented in the `dcc()` function of the `treeClim` package for R (Zang and Biondi 2015). Verification of each significant and stable climate-tree growth relationship was carried out using a split-sample approach where data from half of the period with instrumental climate data were used for calibration and verification was carried out using the remaining data not used in calibration. The data employed in this process were then reversed. Regressions developed for each split sample were assessed through a suite of metrics including calculations of a sign test, product means test, Reduction of Error (RE) (Fritts 1976), and Coefficient of Efficiency (CE) (Briffa *et al.* 1988). A regression was determined for the full period of overlap between the tree-ring and instrumental climate data for the variables that exhibited consistent calibration and verification results for both of the split sample tests.

## RESULTS AND DISCUSSION

Field work for this project spanned two years and resulted in tree-ring samples collected from a total of 368 living trees, 15 stumps, and 17 beams from six historic structures at 46 sites across southwestern Wisconsin during the winters of 2012–13 and 2013–14 (Figure 1b). Crossdating was successful on 731 core samples and cross sections that resulted in 46 site chronologies (Figure 2). Earliest dates ranged from 1677 to 1921 and mean inter-series correlations ( $\bar{r}$ ) ranged from 0.02 to 0.723 (Table 1). No trend existed in a plot of inter-chronology correlations and distance, indicating that distance decay is less important than differences in local site conditions in creating differences among our chronologies (Figure 2). The mean inter-correlation among the 39 site chronologies developed from living trees was 0.56 ( $n > 20$ ,  $p < 0.05$  in all cases), supporting the development of a regional chronology. Convergence of the SSF chronology occurred after 11 iterations, with the final SSF chronology spanning 1677 to 2014 (Figure 3). Sample depth for the regional chronologies was two series from different trees in 1700, 96 series in 1800, and 491 series in 1900.

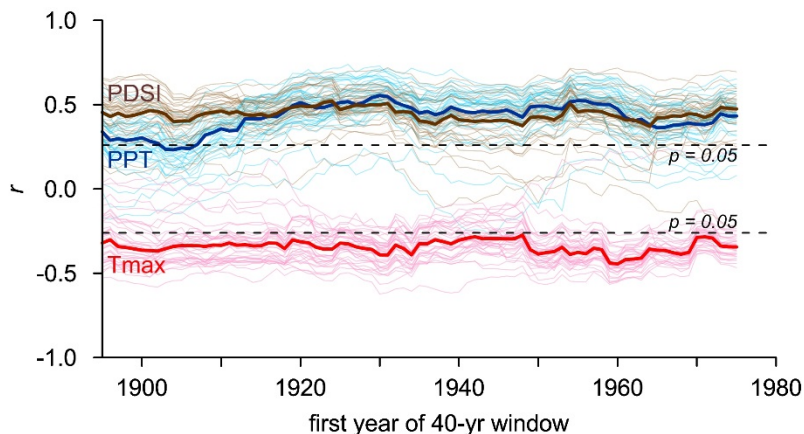


**Figure 2.** Plots of the ARSTAN standardized ring-width index (RWI) chronology for each of 46 sites included in the Driftless Oaks study. The inset scatter plot illustrates site-intercorrelation as a function of distance; the lack of a trend in the scatter plot suggests a regionally coherent pattern of tree growth among the sites.



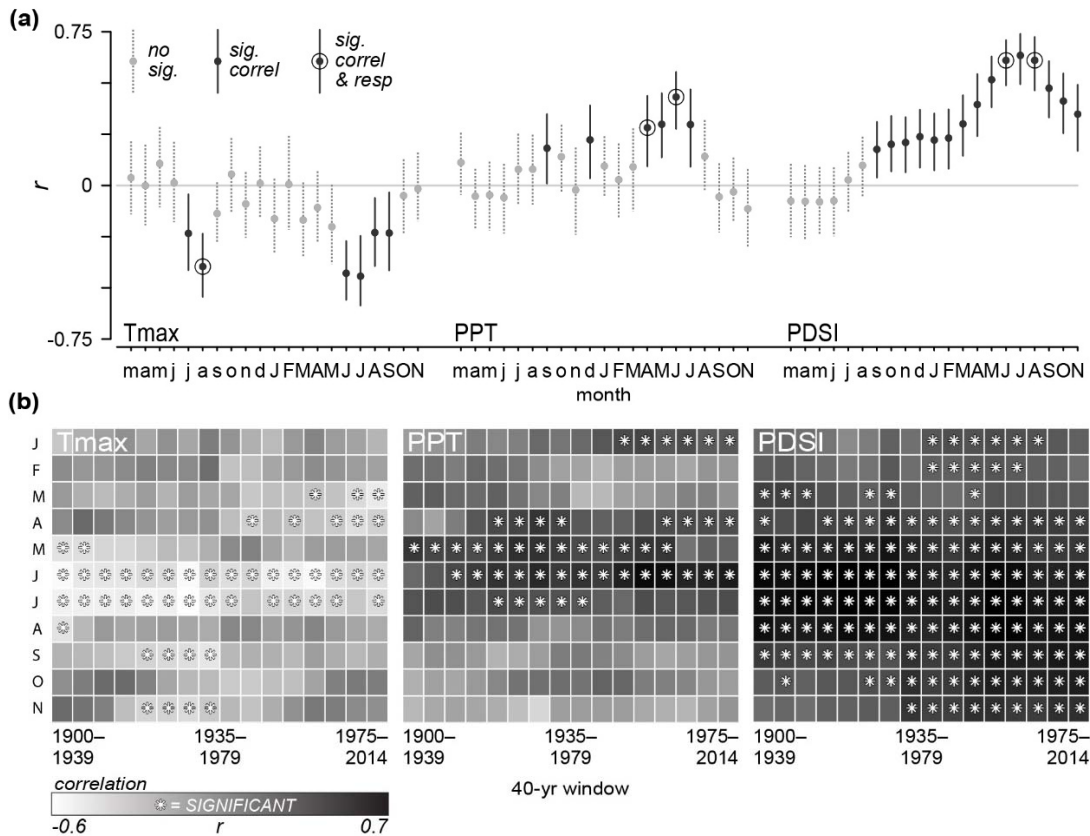
**Figure 3.** The Driftless Oaks regional signal-free (SSF) chronology, including the annual SSF chronology as a gray line overlain with a bold 32 year spline to highlight low frequency variability in the chronology, the expressed population signal (EPS) of the chronology shown in red, and the number of series incorporated in the chronology as gray fill. Dotted lines in the SSF chronology and EPS indicate years when  $EPS < 0.8$  and less confidence can be placed in the chronology.

Correlations between the 40 site chronologies that overlapped by at least 20 years with the seasonalized Wisconsin Division 7 climate variables identified significant ( $n > 93$ ,  $p < 0.05$ ) inverse correlations with June–July maximum temperatures for 37 (mean  $r = -0.34$ ), significant positive correlations with April–June precipitation for 30 (mean  $r = -0.28$ ), and significant positive correlations with June–August PDSI for 34 (mean  $r = 0.37$ ) when compared with the ARSTAN chronologies. Significant correlations were identified between these climate variables and 37 (mean  $r = -0.31$ ), 38 (mean  $r = 0.36$ ), and 39 (mean  $r = 0.40$ ) of the RES chronologies, respectively. Moving correlations data indicated that most site chronologies exhibited significant correlations ( $r > 0.26$ ,  $n > 93$ ,  $p < 0.05$ ) with each variable for the duration of the instrumental record (Figure 4). Overall, correlations with June–August PDSI were the strongest and most consistent over the duration of the instrumental record. Collectively, these results supported the creation of a regional chronology and summer drought as the target variable for reconstruction.

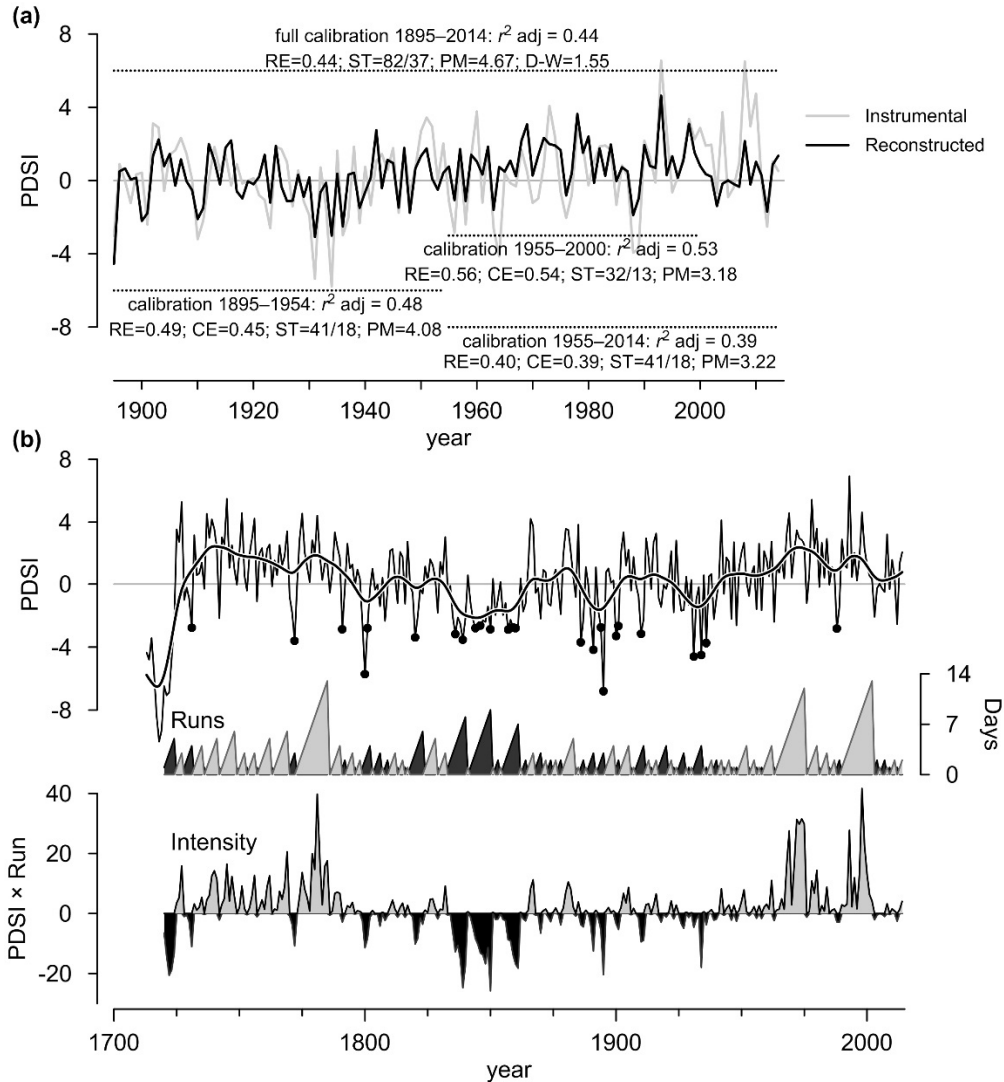


**Figure 4.** Moving correlations between each of 40 individual site chronologies and seasonalized NCDC Wisconsin Division 7 climate variables including June–July maximum temperature ( $T_{max}$ ), April–June precipitation (PPT), and June–August Palmer's drought severity index (PDSI). Thin lines represent correlations for individual chronologies, bold lines indicate the mean correlation across all sites. Data shown are for the RES chronologies and are similar to results with the ARSTAN chronologies (data not shown).

Correlation analysis between the SSF chronology and monthly climate identified a classic moisture-sensitive climate response including significant inverse correlations and response functions with current and previous growing season maximum temperatures, significant positive correlations and response functions with growing season precipitation, and significant positive correlations and response functions with current year PDSI (Figure 5a). Moving correlation and response function analyses indicated a stable relationship between the SSF chronology and June–August PDSI (hereafter referred to as summer PDSI) for the entire instrumental record (Figure 5b). Verification metrics indicated significant and skillful reconstructions of drought for both sides of the split verification, though verification was somewhat weaker for the calibration (Figure 6a). A linear regression transfer function based on the entire instrumental record explained 44% of the variance in instrumental summer drought, with robust verification metrics (Figure 6a). The full Driftless Oaks drought reconstruction extended from 1712–2014 with good reliability and skill (Figure 6b). The occurrence of drought conditions was clustered in time, with the 1700s and 1900s being relatively wet and the 1800s being drier than almost any individual year of the instrumental record. Runs analysis indicated extended pluvial events in the late 1700s and late 1900s. Most of the years within the driest 10% of the last 300 years falling in the mid and late 1800s, during which time a strong drought, relative to the instrumental record, persisted for almost 40 years. The 1900s were extremely wet in terms of both runs and intensity, and the 1700s may have experienced similar conditions. The extreme drought that took place in the mid-1800s would have widespread economic, environmental, and ecological impacts if they were to happen today.



**Figure 5.** Climate-growth relationships exhibited by the Driftless Oaks SSF chronology as (a) correlation and response function analysis results for the period 1895–2014 and (b) as correlations over moving 40-yr windows, overlapped by five years.



**Figure 6.** Reconstruction of NCDC Wisconsin Division 7 June–August PDSI based on the Driftless Oaks SSF chronology. (a) Split calibration and verification results that supported the development of a linear regression based on the entire period of overlap between the chronology and instrumental PDSI data. (b) A 302-year reconstruction of summer PDSI for the Driftless Area of southwest Wisconsin overlain by a 20-year smoothing spline to illustrate low-frequency variations in drought conditions; a runs test showing the number of sequential years of drought and above-average moisture; and drought intensity as represented by the PDSI of each year multiplied by the number of years in the drought.

## CONCLUSIONS AND RECOMMENDATIONS

Pluvials during the 1900s may have set expectations unreasonably high for moisture delivery and crop production in the future. It seems prudent, given the also present possibility for extreme drought conditions to establish for decades at a time, that options should be pursued to incorporate some sort of buffer in the decision making process for on-the-ground activities that land managers pursue.

Furthermore, as technological advances have enabled ever-greater crop yields out of an acre of land the sensitivity to climate has increased (Lobell *et al.* 2014). Given the ubiquitous presence of severe droughts in the past, many of which are linked to the downfall of agricultural societies (Douglass 1929, Stahle *et al.* 1998, Stahle *et al.* 2000, Acuna-Soto *et al.* 2005), it seems prudent to contemplate the susceptibility of our current approaches to resource management and perhaps consider the development of buffers in terms of production that may alleviate some of the societal-scale impacts from future droughts.

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## APPENDIX A

### Publications

1. Allen, S., and E. R. Larson. 2014. The Driftless Oaks: An environmental history of southwest Wisconsin. *Wisconsin Natural Resources* 38:6–7.

### Presentations

<i>Presentation information</i>	<i>No. of attendees</i>
1. Evan R. Larson. 2016. History through the Rings of Trees. Crooked Lake Association Healthy Lakes Meeting, April 24, Deerwood, Minnesota.	30
2. Evan R. Larson and J. Elmo Rawling III. 2015. <i>The environmental history at Ox-Bow</i> . Visiting Faculty Seminar Series, August 13, Saugatuck, Michigan.	30
3. Evan R. Larson. 2015. <i>The profound impacts of invasive earthworms on hardwood forests in Wisconsin</i> . Ralph Nuzum Lecture Series, Kickapoo Valley Reserve, June 25, La Farge, Wisconsin.	60
4. Evan R. Larson and Sara Allen. 2015. <i>The Driftless Oaks Project: A reception for landowners</i> . University of Wisconsin-Platteville Tree-Ring, Earth, and Environmental Sciences Laboratory, May 5, 2015, Platteville, Wisconsin.	40
5. Evan R. Larson. 2015. <i>The Good Oak: Stories of Midwestern drought and hydrologic change through tree rings</i> . Department of Geography Colloquium, Northern Illinois University, March 6, DeKalb, Illinois.	40
6. J. Elmo Rawling III, Evan R. Larson, and Sara Allen. 2015. <i>New chronologies from the Great Lakes cutover: Dendroecology of a mid-1800s pier in the old harbor of the Kalamazoo River along the southeast shores of Lake Michigan</i> . Annual Meeting of the Association of American Geographers, April 20–25, Chicago, Illinois.	60
7. Jaime A. Teutschmann*, Sara Allen, and Evan R. Larson. 2015. <i>Ring anomalies in the Driftless Oaks: A proxy for extraordinary events?</i> Annual Meeting of the Association of American Geographers, April 20–25, Chicago, Illinois.	120+
8. Jamie Jefferson* and Evan R. Larson. 2015. <i>The story of land and people through the lens of tree rings: Dendroarchaeology of the Gratiot House, southwest Wisconsin</i> . Annual Meeting of the Association of American Geographers, April 20–25, Chicago, Illinois.	60
9. Jessica Kleckner* and Evan R. Larson. 2015. <i>Historical ecology of an oak savanna in Memorial Park on the University of Wisconsin-Platteville campus</i> . Annual Meeting of the Association of American Geographers, April 20–25, Chicago, Illinois.	120+
10. Sara Allen and Evan R. Larson. 2015. <i>The Good Oak: Establishing the long-term range of variability in drought conditions for southwest Wisconsin using oak tree chronologies</i> . Annual Meeting of the Association of American Geographers, April 20–25, Chicago, Illinois.	45
11. Evan R. Larson. 2015. <i>Stories, students, and TREES: An introduction to tree-ring research through some of the spectacular accomplishments of UW-Platteville undergraduates working in the Tree-Ring, Earth, and Environmental</i>	100

<i>Sciences Laboratory</i> . University of Wisconsin-Platteville Retirees Breakfast, January 28, Platteville, Wisconsin.	
12. Evan R. Larson. 2015. <i>High-impact educational experiences through the UW-Platteville TREES Lab</i> . Optimists International Club, January 22, Platteville, Wisconsin.	20
13. Sara Allen and Evan R. Larson. 2014. <i>Establishing the long-term range of variability in drought conditions for southwest Wisconsin using oak tree chronologies</i> . Connections in Nature Student Research Symposium, Riveredge Nature Center, November 8, Saukville, Wisconsin.	50
<b>Total</b>	<b>775+</b>

### **Students who received salary through the grant**

1. Jamie Jefferson, graduated spring 2014, currently employed by Americorp
2. Jaime Teutschmann, graduated spring 2015, applying to graduate programs in biology

In addition to these students who received salary through this grant, over 30 students participated in field and laboratory research for this project.

### **Impact of this work**

The overall impact of this research was tremendous. It enabled a recent UW-Platteville graduate, Sara Allen, to fully engage in scientific research that expanded her experiences and has prepared her for graduate school. It provided authentic research experiences to numerous UW-Platteville students who otherwise have limited opportunities to gain undergraduate research experience. It helped craft a portrait of drought over the Driftless Area of Wisconsin that holds important lessons for how we plan for the future. Perhaps most importantly, however, this research connected faculty, staff, and students from a primarily undergraduate campus to over 240 landowners in a powerful illustration of the value and services provided by institutions of higher education to the people of Wisconsin. The interest in this project was palpable, and dozens of conversations that began with “I didn’t know people in Platteville were doing this type of work...” ended following extended conversations about the land and water of southwest Wisconsin. This impact was epitomized in the final thank you gathering where we invited all of the landowners who had participated in the project to tour the TREES Lab and to gather for a meal, provided by the TREES Lab, to share stories and listen to a presentation that reported the outcome of all of this work. This project captured the spirit of the Wisconsin Idea and engaged people with a range of backgrounds and interests on the topics of climate and climate change through the neutral, yet powerful, medium of tree rings.

# Impacts of Climatic and Land Use Changes on Streamflow and Water Quality in the Milwaukee River Basin

## Basic Information

<b>Title:</b>	Impacts of Climatic and Land Use Changes on Streamflow and Water Quality in the Milwaukee River Basin
<b>Project Number:</b>	2013WI314B
<b>Start Date:</b>	3/1/2014
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	4th
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Hydrology, Water Quality, Models
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Woonsup Choi, Changshan Wu

## Publication

1. Deng, Y. and C. Wu. Development of a Class-based Multiple Endmember Spectral Mixture Analysis (CMESMA) Approach for Analyzing Urban Environments. Remote Sensing, In Press.

# Completion Report - Impacts of Climatic and Land Use Changes on Streamflow and Water Quality in the Milwaukee River Basin

**Reporting Period:** 3/1/2015 - 2/29/2016

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## **Project**

WR13R004 - Impacts of climatic and land use changes on streamflow and water quality in the Milwaukee River basin.

## **Principle Findings and Significance**

During the period, selected water resources variables were examined between different scenario combinations of land use and climatic changes.

### Mean and Variability of Streamflow

- Streamflow changes vary widely between global climate models (GCMs)
- Streamflow from the land use scenario was almost identical to that from the baseline, with no changes larger than 2%
- The seasonal pattern does not change much with land use or climatic changes

### Low Flow Indices (7Q10)

- Compared to mean streamflow, 7Q10 is projected to change (mostly decrease) more substantially with the land use scenario
- Climate change is projected to have very large impacts on 7Q10
- Increases and decreases are almost evenly split between GCMs

### Sediment Export

- Similar to streamflow, sediment export barely changes with the land use scenario, mostly decreasing
- It is projected to increase quite substantially with all GCMs
- Sediment export shows a similar seasonal pattern to streamflow and much larger variability among the GCMs and between warm and cold seasons

## **Number of Personnel Involved**

2 Participating faculty/staff

0 Supported post-docs

**Students Supported**

No students reported.

**Conference Participation**

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**Title**

Annual Meeting of the Association of American Geographers

**Location**

Chicago, IL

**Dates**

23 Apr 2015

**Number of supported students attending**

1

**Presentations by Students**

Impacts of Climate Change on Hydrological Processes and Uncertainties from Climate Models in the Milwaukee River Basin, Wisconsin

**Journal Articles and Other Publications**

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**Title**

Effects of Urban Imperviousness Scenarios on Model-Simulated Surface Flow

**Type of Publication**

Book or Monograph (Peer-reviewed)

**Complete Citation**

Pan, F. and W. Choi, "Effects of Urban Imperviousness Scenarios on Model-Simulated Surface Flow," in review for Applied Geography

**Awards and Achievements**

No awards and achievements reported.

**Research Patent or Copyright**

No research patents or copyrights reported.

**Completion Summary**

The results from the study suggest that the current pace of urban growth would not pose much threat to the water resources in the area. Therefore, it is recommended that local authorities control the pace of urban growth not to

exceed what is projected in this study. Considering that low flow indices responded more sensitively to climate change than mean streamflow, measures to improve resilience to drought conditions are recommended. In addition, more thorough research on drought in the Milwaukee River basin is recommended. Finally, it would be necessary to reevaluate the total maximum daily load guidelines and take action to reduce soil erosion.

# Impacts of Climate and Land Use Changes on Streamflow and Water Quality in the Milwaukee River Basin

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## PROJECT SUMMARY

Title: Impacts of Climate and Land Use Changes on Streamflow and Water Quality in the Milwaukee River Basin

Project ID: WR13R004

### Investigators:

- Principal Investigator: Dr. Woonsup CHOI (Associate Professor, Department of Geography, University of Wisconsin-Milwaukee)
- Co-Principal Investigator: Dr. Changshan WU (Professor, Department of Geography, University of Wisconsin-Milwaukee)
- Research Assistant: Feng PAN (Graduate Student, Department of Geography, University of Wisconsin-Milwaukee)
- Research Assistant: Wenliang LI (Graduate Student, Department of Geography, University of Wisconsin-Milwaukee)

Period of Contract: 1 March 2013 to 29 February 2016

### Background/Need:

The Milwaukee River basin is one of the most urbanized basins in Wisconsin. It is common knowledge that urbanization generally results in higher average and extreme streamflow, diminishing low flows, and higher loads of non-point source pollutants. The July 2010 flood in the metropolitan Milwaukee area followed by the release of pollutants to Lake Michigan is a good example of the effects of urbanization on streamflow and water quality. Global climate change is another factor that significantly affects the quantity and quality of freshwater resources, and will certainly affect the Milwaukee River basin. Rising temperature, increasing saturation vapor pressure of the air, and increasing variability of precipitation will modify the storage and flux of water in the hydrological cycle. The direction and magnitude of the change, however, largely depend on individual basin characteristics. Temperature, particularly winter temperature, is projected to rise across Wisconsin throughout the 21<sup>st</sup> century. There is a high level of certainty that winter precipitation will increase statewide by about 25% by mid-century.

Unfortunately, very few studies have investigated the climate change impacts on the Milwaukee River basin. There have been no comprehensive efforts to study the aforementioned problems in the Milwaukee River basin. A thorough climate change impact assessments on freshwater resources should consider the effects of rising temperature, rising precipitation, changing seasonality, and extreme weather events, in conjunction with land cover changes.

### Objectives:

The objective of the research was to investigate the effects of climate and land use changes on hydrological and water quality parameters of the Milwaukee River basin. The research sought to address the following questions:

- (1) What are the plausible land use scenarios for the Milwaukee River basin over the coming decades?
- (2) How will the hydrological and water quality parameters respond, individually and collectively, to different climate and land use scenarios?

Methods: The study consisted of administering a hydrological model to simulate water resources variables using a range of climate and land use scenarios. The Hydrological Simulation Program—Fortran (HSPF) was calibrated to use scenarios representing the baseline (1961-2000) and future (2046-2065) climate and land use conditions. Climate scenarios were obtained from the output of nine global climate

models (GCMs) and land use scenarios were obtained from the output of a land use change model that the investigators developed. The study focused on three aspects of water resources: mean streamflow, low flow indicated by 7Q10 and 7Q2, and sediment export.

#### Results and Discussion:

The nine GCMs consistently projected warmer climate by the mid-2050s for the Milwaukee River basin. Annual precipitation was projected to increase with large seasonal variability. The land use change model developed for the study suggested that urban areas would increase by more than 8% with a decrease in most other land uses.

The changes in mean annual runoff were inconclusive. The changes were very small if only land use scenarios were considered. When climate scenarios were used, the changes ranged between -29.5% and +18.3% depending on the GCM. Because land use change impacts are quite small, considering the impact of both climate and land use scenarios did not produce a very different result.

Low flow indices such as 7Q10 and 7Q2 showed more sensitivity to the scenarios than mean annual runoff. Low flow indices were much more sensitive to climate scenarios than land use scenarios. When considering both climate and land use change, 7Q10 could decrease by up to 74% and increase by up to 37%. For 7Q2, it was 60% and 18%, respectively. The more severe low flow index (7Q10) was observed to show a bigger sensitivity.

Sediment export was projected to change little with land use scenarios but the effect of climate scenarios was more substantial. All the GCMs projected increased sediment export, with larger percentage increase compared to mean annual runoff.

#### Conclusions/Implications/Recommendations:

The results from the study suggest that the current pace of urban growth would not pose much threat to the freshwater resources in the area. Therefore, it is recommended that local authorities control the pace of urban growth not to exceed what is projected in this study. Considering that low flow indices responded more sensitively to climate change than mean streamflow, measures to improve resilience to drought conditions are recommended. In addition, more thorough research on the risk and impact of drought in the Milwaukee River basin is recommended. Finally, it would be necessary to reevaluate the total maximum daily load guidelines and take actions to reduce soil erosion.

Key Words: runoff, low flow, sediment load, climate change, urban growth

## INTRODUCTION

The Milwaukee River basin is one of the most urbanized river basins in Wisconsin (Wisconsin Department of Natural Resources 2001), and it is well-known that increased urbanization generally results in higher average and extreme flows, diminishing low flows, and higher non-point source pollutant loading (e.g. Choi and Deal 2008, Chang 2007, Wang et al. 2005). The July 2010 flood in the metropolitan Milwaukee area followed by the massive release of pollutants to Lake Michigan is a good example of the effects of urbanization on streamflow and water quality. The National Land Cover Database reveals that urban areas increased by 87% in the Milwaukee River basin between 1992 and 2006, and could continue in the following decades.

Global climate change significantly affects the quantity and quality of freshwater resources (Arnell and Liu 2001) and will certainly affect the Milwaukee River basin. Rising temperature, increasing saturation vapor pressure of the air, and increasing variability of precipitation will modify the storage and flux of water in the hydrological cycle. The direction and magnitude of the changes largely depend on individual basin characteristics (Chang and Jung 2010). Temperature, particularly winter temperature, is projected to rise across Wisconsin throughout the 21<sup>st</sup> century. There is a high level of certainty that winter precipitation will increase statewide by about 25% by mid-century (Wisconsin Initiative on Climate Change Impacts 2011). Rising temperature is expected to cause increased evaporation rates and water temperature. Increases in winter and spring precipitation will likely cause large runoff events leading to increased sediment and nutrient transport (Wisconsin Initiative on Climate Change Impacts 2011). Unfortunately, not much research has been done to understand climate change impacts on the Milwaukee River basin. No relevant peer-reviewed article was found on the ISI Web of Knowledge<sup>SM</sup> with ‘Milwaukee River’ and ‘climate change’ as keywords. A study on the Fox River basin, located southwest of the Milwaukee River basin, finds that climate change would cause generally reduced average and low flows (Bekele and Knapp 2010).

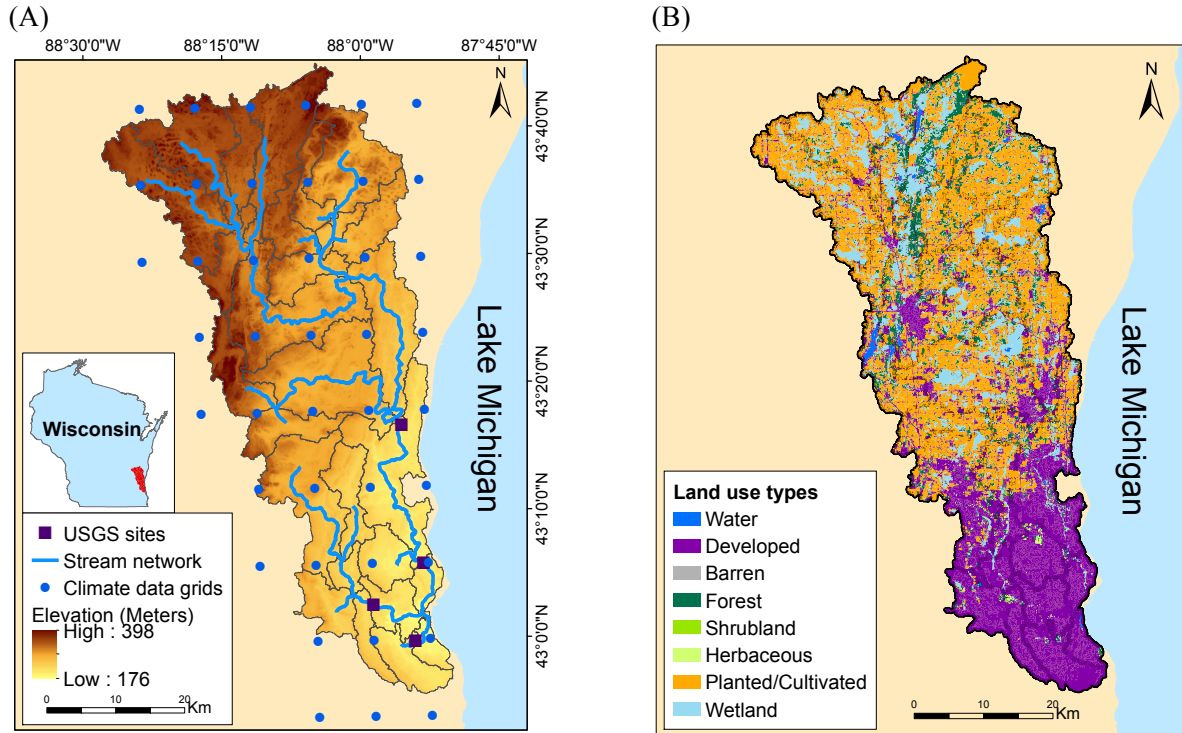
Nevertheless, there have been some isolated efforts to study the Milwaukee River basin. An investigation finds that precipitation and baseflow generally increased in southeastern Wisconsin during 1950-2006 (Choi et al. 2016, Wisconsin Initiative on Climate Change Impacts 2011). Other studies conduct hydrological simulations to investigate the effects of new residential, industrial and commercial development (Camp Dresser & McKee 2000) and best management practices for stormwater runoff in the Milwaukee area (Milwaukee Metropolitan Sewerage District 2007). A comprehensive climate change impact assessments on water resources should consider the effects of rising temperature, rising precipitation, changing seasonality, and extreme weather events together in conjunction with land use changes. This study assesses climate change impacts on the Milwaukee River basin using newly available data while taking into consideration the spatial dynamics of land use.

## PROCEDURES AND METHODS

### Study Area

We chose the Milwaukee River basin (2 330 km<sup>2</sup>) located in southeastern Wisconsin as our study area (Figure 1). It is part of the Lake Michigan basin and covers 13 cities, 32 towns, and 24 villages. The southern portion of the basin is heavily populated and urbanized, with more than 1 million inhabitants. The land cover in the northern portion consists primarily of agricultural land. The basin’s topography is comprised of rolling moraine over bedrock, sloping downward from northwest (inland) to southeast (lakeshore) (Wisconsin Department of Natural Resources 2001). There are three major rivers in the Milwaukee River basin, namely Milwaukee, Menomonee, and Kinnickinnic. The Menomonee and Kinnickinnic rivers merge with the Milwaukee River in downtown Milwaukee (approximately 43°/87°50’

in Figure 1(A)) and the Milwaukee River empties into Lake Michigan. The Milwaukee River flows from north and northwest to south and the Menomonee from northwest to southeast, and both rivers flow through rural and urban areas. On the other hand, the Kinnickinnic River flows from southwest to northeast through a heavily urbanized area.



**Figure 1. (A) The boundary, major streams, and elevations of the Milwaukee River basin. Its location in the state of Wisconsin is shown in the inset map. Also shown are the grid points of the historical climate data and the U.S. Geological Survey (USGS) streamflow measurement sites. (B) Land cover of the Milwaukee River basin from NLCD 2001**

## Water Resources Variables

The study focused on three important variables of water resources: mean streamflow, low flow indicated by 7Q10 and 7Q2, and sediment export. Mean streamflow was obtained by calculating an average of all daily flow values for the entire simulation period. The 7Q10 is an indicator of low flow widely used in the U.S. as a hydrologically-based design flow, and refers to the lowest 7-day average flow with a 10 percent probability of it occurring in any given year (i.e. 10-year recurrence interval) (Smakhtin 2001, U.S. Environmental Protection Agency 2013). Similarly, the 7Q2 is the lowest 7-day average flow with a 50 percent probability of it occurring in any given year. Sediment export measures the mass of sediment exported from the land surface to the stream per day. The selected variables addressed part of the water resources research priorities identified by the Wisconsin Initiative on Climate Change Impacts (2011).

## Hydrological Model

The study employed the Hydrological Simulation Program—Fortran (HSPF) (Duda et al. 2012) to simulate streamflow and water quality. We used the WinHSPF, a Windows® interface of HSPF and available as part of the U.S. Environmental Protection Agency's Better Assessment Science Integrating point & Non-point Sources (BASINS) Version 4.1 (U.S. Environmental Protection Agency 2013). HSPF consists of three modules, namely PERLND, IMPLND, and RCHRES. In HSPF, the study area is divided

into subbasins according to topography, and each subbasin contains pervious and impervious land segments and a stream channel (and/or a reservoir). The PERLND module simulates hydrological processes on pervious land segments, whereas IMPLND is used for impervious land segments. The RCHRES module simulates hydraulic processes in a channel or a reservoir.

The HSPF requires hourly meteorological and physiographical data to operate. The software requires a minimum of two types of meteorological data—precipitation and evapotranspiration. When evapotranspiration data is not available, it is estimated using related variables such as air temperature, wind speed, and cloud cover. The meteorological data is available for the continental U.S. from the HSPF website and other sources. For our study, we used wind speed and cloud cover data downloaded from the HSPF website and extracted precipitation and temperature data from the gridded historical daily precipitation and maximum/minimum temperature datasets produced by researchers at the University of Wisconsin-Madison (Serbin and Kucharik 2009). The precipitation and temperature datasets were developed by interpolating weather stations data across Wisconsin with about 8-km grid spacing (Figure 1(A)) for the period 1950-2006. An algorithm in the BASINS module was used to produce hourly data from the daily data.

The land use/cover data for the baseline period was obtained from the 2001 National Land Cover Database (NLCD) produced by the U.S. Geological Survey (USGS) at a spatial resolution of 30m × 30m. The NLCD 2001 was derived from satellite imageries from the Multi Resolution Land Characteristics Consortium (Homer et al. 2012). Figure 1(B) shows the NLCD 2001 clipped for the Milwaukee River basin. The land cover classes have been aggregated for simplicity and the aggregated classes were used for HSPF.

**Table 1. HSPF model evaluation parameters for the calibration and validation periods at four USGS streamflow gage sites in the Milwaukee River basin. Site ID numbers are shown in parentheses.**

	Menomonee (04087120)		Milwaukee (04087000)	
	Calibration	Validation	Calibration	Validation
RE (%)	2.07	1.43	2.13	4.87
NSE	0.67	0.48	0.71	0.54
	Cedarburg (04086600)		Kinnickinnic (04087159)	
	Calibration	Validation	Calibration	Validation
RE (%)	3.31	3.45	8.79	13.00
NSE	0.70	0.60	0.62	0.39

The model parameters were calibrated against the measured streamflow data for the period 1986-1995, and validated for the period 1996-2005. The streamflow data were obtained from the four USGS sites shown in Figure 1(A). From north to south in the map, they are referred to as Cedarburg, Milwaukee, Menomonee, and Kinnickinnic, respectively. The selection of the calibration period was based on the availability of the NLCD and streamflow data. The comparison with the measured streamflow included calculation of the relative error (RE) and the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970). The RE refers to the percentage difference between the simulated mean runoff and the measured mean runoff, and indicates the overall bias of the model. The NSE measures goodness-of-fit between the two time series, and has a range of  $-\infty$  to unity. Unity indicates a perfect fit, and a negative value indicates that the mean of the measured runoff is a better predictor than the model.

Model evaluation parameters for the calibration and validation periods are presented in Table 1. With the exception of Kinnickinnic, the RE was less than 5%, indicating very low overall bias. NSE values for the calibration period ranged from 0.62 (Kinnickinnic) to 0.71 (Milwaukee), and they were a little lower for

the validation period across the sites. Overall, the model reproduced accurately the mean streamflow and did a reasonable job with goodness-of-fit.

Due to limited data availability, HSPF was not calibrated for sediment export. We compared the available observed total suspended solids data to the simulated total suspended solids, and the relative errors were 3.26% and 9.57% at the annual and monthly scale, respectively.

## Climate Scenarios

Climate scenarios were derived from a climate model-based dataset created under the Wisconsin Initiative on Climate Change Impacts. The dataset was produced by statistically downscaling the output from nine global climate models (GCMs) (Table 2) with approximately 10-km grid spacing. Statistical downscaling refers to a procedure that finds statistical relationships between macro-scale atmospheric conditions (such as pressure fields) and micro-scale ground-level measurements (such as near-surface air temperature) in order to transform the coarse-resolution GCM-simulated meteorological variables to the finer resolution needed for the study. The nine GCMs were statistically downscaled using the macro-scale atmospheric data from the National Center for Environmental Prediction/National Center for Atmospheric Research (Kalnay et al. 1996) and ground-level measurements from the National Weather Service's Cooperative Observer Program stations (for details, see Notaro et al. 2011).

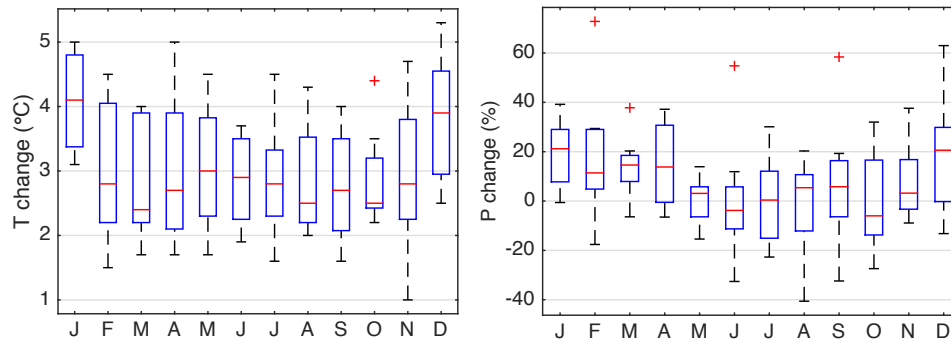
**Table 2. GCMs used for climate scenarios in the study**

Acronym	Institute and country	Model name
cccma_cgcm3_1	Canadian Center for Climate Modelling and Analysis, Canada	The Third Generation Coupled Global Climate Model
cnrm_cm3	Centre National de Recherches Meteorologiques, France	Coupled Global Climate Model version 3
csiro_mk3_0	Commonwealth Scientific and Industrial Research Organisation, Australia	Mark 3.0
csiro_mk3_5	Commonwealth Scientific and Industrial Research Organisation, Australia	Mark 3.5
gfdl_cm2_0	Geophysical Fluid Dynamics Laboratory, USA	Coupled Model, version 2.0
giss_model_e_r	Goddard Institute for Space Studies, USA	Model E/Russell
miub_echo_g	Meteorological Institute, University of Bonn, Germany	ECHO-G = ECHAM4 + HOPE-G
mpi_echam5	Max-Planck-Institut for Meteorology, Germany	ECHAM model, Version 5
mri_cgcm2_3_2a	Meteorological Research Institute, Japan	Coupled General Circulation Model, Version 2.3.2a

The downscaled GCM dataset includes late-20<sup>th</sup> century simulations (1961-2000) and mid-21<sup>st</sup> century projections (2046-2065) using the Special Report on Emissions Scenarios (Nakicenovic and Swart 2000) A1B greenhouse gas emissions scenario. In this scenario, fossil CO<sub>2</sub> emissions begin to decrease after the mid-21st century and there is a moderate increase in atmospheric CO<sub>2</sub> concentrations. Of the six SRES emissions scenarios (A1B, A1FI, A1T, A2, B1, and B2), the A1B scenario lies in the middle.

All the GCMs predicted an increase in temperature by 2046-2065 with respect to the monthly baseline (Figure 2); increases were particularly large in December and January, with a median value of approximately 4°C. Precipitation was generally projected to increase as well by 2046-2065, particularly in the colder months; January and December were the months with the highest increase, with a median value

of more than 20%. Regarding the changes between May and November, median values varied around zero.



**Figure 2. Distribution of mean monthly changes in temperature and precipitation between 1961-2000 and 2046-2065 projected by the nine GCMs. The horizontal lines within the boxes indicate lower quartile, median, and upper quartile values. Whiskers represent the most extreme values within 1.5 times the interquartile range. Plus (+) signs denote outliers. Same for other box-whisker plots.**

## Land Use Scenarios

We developed two Cellular Automata models to simulate the spatial dynamics of residential and commercial land uses. These models are composed of four parts, including (1) global residential/commercial expansion probability calculation, (2) neighborhood effect, (3) constraints of future development, and (4) random factors. To calculate the global probability of residential/commercial expansion, a logistic regression model was constructed using driving factors including elevation, slope, distance to the nearest city, distance to lake, distance to railway, distance to river, distance to road, distance to village, and population density. With the collected residential and commercial data for the basin, we constructed and calibrated the model for the period 1990-2000, and the years 2000-2005 was employed for the model validation. With all identified parameters, the residential and commercial growth models were applied to a Cellular Automata model to simulate residential and commercial growth in 2050. Results indicated that both the residential and commercial growth models worked well with kappa values of 97.25% and 93.50%, respectively. The land use change model projects a modest increase (8.25%) in developed lands by the year 2050 and forest, shrubland, and other vegetation land covers are projected to decrease.

**Table 3. Land use statistics and projected changes by the year 2050**

Land use	Current (km <sup>2</sup> )	2050 (km <sup>2</sup> )	Change (%)
Water	21.21	20.94	-1.27
Developed	714.28	773.18	8.25
Barren	1.83	1.85	1.09
Forest	240.47	224.48	-6.65
Shrubland	15	14.02	-6.53
Herbaceous	15.87	15	-5.48
Planted/Cultivated	949.56	911.03	-4.06
Wetlands	261.71	259.45	-0.86

## RESULTS AND DISCUSSION

The calibrated HSPF model was run with temperature and precipitation data from the downscaled dataset under different land use conditions. The simulations with different climate and land use scenarios are given in Table 4. We report the results from the simulations by the water resources variables for the entire basin.

**Table 4. Hydrological modeling experiment setup consisting of different climate and land use scenarios**

Modeling experiments	Acronym	Temperature and precipitation data	Land use data
Baseline	Baseline	Downscaled 1961-2000	2000
Land use change only	LUC	Downscaled 1961-2000	2050
Climate change only	CC	Downscaled 2046-2065	2000
Climate and land use changes	CLUC	Downscaled 2046-2065	2050

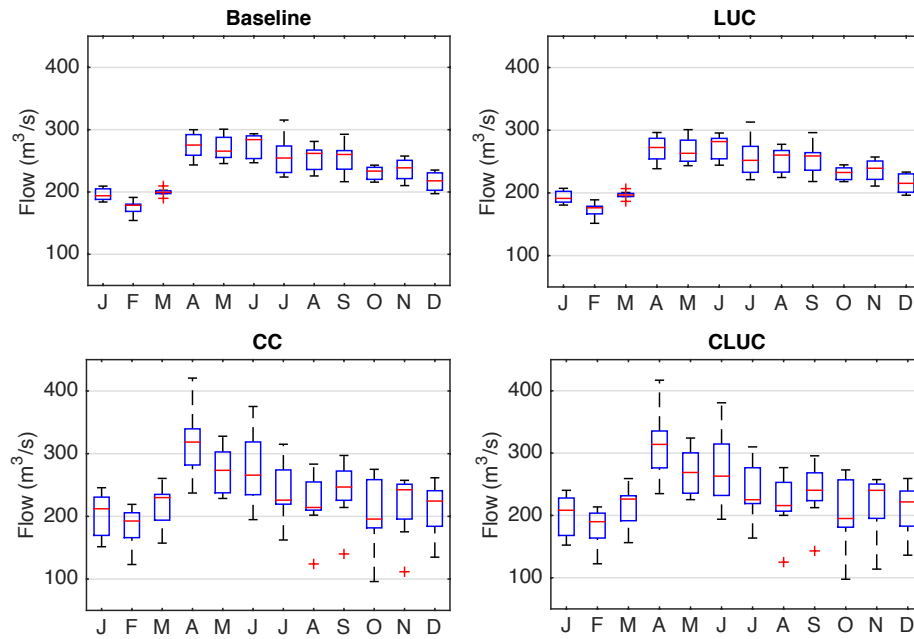
### Mean and Variability of Streamflow

The mean streamflow results obtained from the different modeling experiments are presented in Table 5. For Baseline, the smallest flow of 220 m<sup>3</sup>/s was simulated with gfdl\_cm2\_0, and the largest flow of 256.4 m<sup>3</sup>/s with csiro\_mk3\_5. Streamflow from LUC was almost identical to that from Baseline, with no changes larger than 2%. On the other hand, streamflow changes varied widely between GCMs in CC, from 155 m<sup>3</sup>/s (gfdl\_cm2\_0) to 278.6 m<sup>3</sup>/s (giss\_model\_e\_r). The largest and smallest flows also reflected the largest percentage increase (18.3%) and decrease (29.5%), respectively. The different GCMs showed equal possibilities of both increase and decrease in streamflow. The magnitudes of mean streamflow from CLUC were slightly smaller than those from CC, reflecting the small decreases in LUC.

**Table 5. Simulated mean streamflow (m<sup>3</sup>/s) from different modeling experiments. Percentage changes from Baseline are shown in parentheses.**

GCM	Baseline	LUC	CC	CLUC
ccma_cgcm3_1	237.7	235.1 (-1.1)	239.4 (0.7)	236.7 (-0.4)
cnrm_cm3	224.4	224.4 (0.0)	262.0 (16.8)	260.2 (16.0)
csiro_mk3_0	236.5	235.1 (-0.6)	246.7 (4.3)	244.5 (3.4)
csiro_mk3_5	256.4	255.2 (-0.4)	205.4 (-19.9)	204.0 (-20.4)
gfdl_cm2_0	220.0	218.0 (-1.0)	155.0 (-29.5)	155.3 (-29.4)
giss_model_e_r	235.4	232.6 (-1.2)	278.6 (18.3)	276.0 (17.2)
miub_echo_g	229.1	227.9 (-0.5)	226.8 (-1.0)	224.4 (-2.0)
mpi_echam5	246.3	244.3 (-0.8)	244.0 (-0.9)	240.0 (-2.6)
mri_cgcm2_3_2a	244.4	243.7 (-0.3)	254.0 (3.9)	250.9 (2.7)

Mean monthly flow results from the modeling experiments are presented in Figure 3. Baseline streamflow tended to peak in spring and summer and decrease in winter. Streamflow in July show the largest variability among the GCMs. The seasonal pattern did not change much with the inclusion of land use or climate changes. The results from LUC were almost identical to Baseline, because the same GCMs were used. In CC and CLUC, increased inter-model variability was very noticeable. Variability increased across the year, particularly in the months of April, June and October. When it comes to the median values (red lines in the boxes), April stood out compared to May and June. Streamflow in April was projected to increase not only with respect to Baseline but also compared to May and June, resulting in more contrast between spring and summer. On the other hand, streamflow in July and August was projected to decrease from the Baseline and end up lower than June and September.



**Figure 3. Distribution of simulated mean monthly streamflow according to the nine GCMs**

### Low Flow Indices

When it comes to 7Q10, the smallest variation was obtained with *csiro\_mk3\_5* and the largest variation with *giss\_model\_e\_r* for Baseline (Table 6 upper panel). The *csiro\_mk3\_5* model produced the largest mean annual flow but the smallest 7Q10 of all the GCMs, indicating larger variability of daily streamflow than other GCMs. In LUC, 7Q10 was projected to change (mostly decrease) more than mean streamflow. The largest percentage decrease was projected with *csiro\_mk3\_0* (11.5%), whereas increases were quite small (1.5% with *mpi\_echam5*). Climate change was projected to have very large impacts on 7Q10. It was projected to increase by up to 41.9% (*giss\_model\_e\_r*) and decrease by up to 71.2% (*csiro\_mk3\_5*). Increases and decreases of 7Q10 were almost evenly split between the GCMs (4 and 5 respectively). The CLUC scenario showed mostly decreases. The smallest 7Q2 values were obtained with *csiro\_mk3\_0* and the largest with *mri\_cgcm2\_3\_2a* for Baseline (Table 6 lower panel). In most of the cases 7Q2 was projected to change in the same direction as 7Q10 but generally with smaller percentage changes.

### Sediment Export

The results of simulated sediment export in the four experiments are presented in Table 7. In Baseline, the largest and smallest results were obtained with *csiro\_mk3\_5* and *gfdl\_cm2\_0*, respectively. Like streamflow, sediment export values barely changed in LUC, mostly showing a decreasing trend. However, it was projected to increase substantially with all GCMs in CC, from 11.4% (*giss\_model\_e\_r*) to 96.2% (*miub\_echo\_g*). Increase in values was slightly lower with CLUC than CC.

Sediment export showed a similar seasonal pattern to streamflow, much larger variability among the GCMs, and between warm and cold seasons (Figure 4). In Baseline, sediment export tended to increase in spring and summer with larger inter-GCM variability. It was quite low in the winter months of December, January and February, and the variability among the GCMs was negligible. Sediment export figures changed slightly in the LUC run, particularly in March, May and June. The median value decreased slightly in June. Noticeable changes were found with the CC and CLUC runs. In the CC run, the median, interquartile range (height of the boxes in the graph), and outliers (cross marks in the graph) of mean

monthly sediment export generally increased. April, June, and September showed remarkable increases whereas March and August showed decreases. Sediment export also showed general increases during the winter months. The CLUC showed a result very similar to CC, with slight differences in June and September. A study of the Maumee River basin in northwestern Ohio (Verma et al. 2015) reports climatic and streamflow changes similar to this study, but sediment export is projected to decrease in warmer months with lower streamflow. In this study, decreases in warmer months were not noticeable, which warrants further investigation.

**Table 6. Simulated 7Q10 (upper panel) and 7Q2 (lower panel) from different modeling experiments. Percentage changes from Baseline are shown in parentheses.**

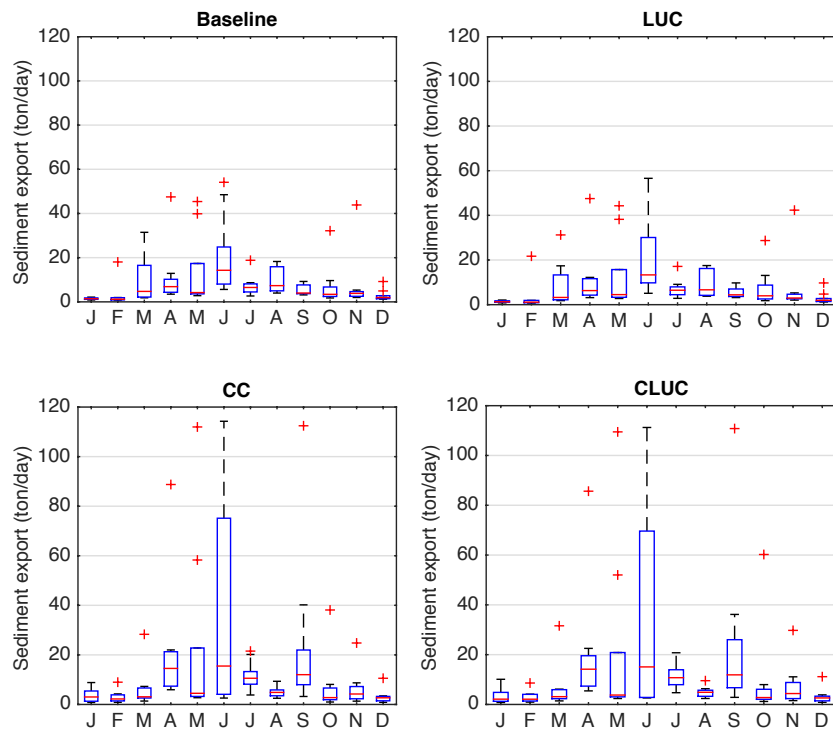
GCM	Baseline	LUC		CC		CLUC	
cccma_cgcm3_1	36.6	35.7	(-2.5)	34.0	(-7.0)	28.6	(-21.8)
cnrm_cm3	36.3	33.3	(-8.3)	37.0	(2.1)	34.8	(-3.9)
csiro_mk3_0	23.2	20.6	(-11.5)	29.7	(27.9)	29.2	(25.6)
csiro_mk3_5	21.1	21.4	(1.2)	6.1	(-71.2)	5.4	(-74.2)
gfdl_cm2_0	31.2	28.8	(-7.6)	10.3	(-67.1)	9.0	(-71.3)
giss_model_e_r	44.4	41.1	(-7.4)	63.0	(41.9)	61.0	(37.4)
miub_echo_g	44.3	44.1	(-0.6)	21.1	(-52.3)	18.4	(-58.4)
mpi_echam5	27.9	28.4	(1.5)	36.2	(29.6)	34.1	(22.2)
mri_cgcm2_3_2a	36.9	37.1	(0.4)	42.3	(14.5)	42.3	(14.5)

GCM	Baseline	LUC		CC		CLUC	
cccma_cgcm3_1	71.7	66.9	(-6.7)	65.3	(-9.0)	61.1	(-14.7)
cnrm_cm3	75.8	75.5	(-0.4)	79.7	(5.2)	75.4	(-0.5)
csiro_mk3_0	58.8	59.3	(0.8)	58.4	(-0.8)	55.0	(-6.5)
csiro_mk3_5	70.8	69.6	(-1.7)	48.0	(-32.2)	47.1	(-33.4)
gfdl_cm2_0	69.0	68.6	(-0.5)	28.6	(-58.6)	27.4	(-60.2)
giss_model_e_r	78.3	76.4	(-2.3)	94.0	(20.1)	92.0	(17.6)
miub_echo_g	71.5	66.7	(-6.6)	51.2	(-28.4)	48.5	(-32.1)
mpi_echam5	75.5	74.5	(-1.3)	82.7	(9.6)	77.3	(2.5)
mri_cgcm2_3_2a	78.9	77.5	(-1.8)	86.6	(9.7)	81.2	(2.9)

**Table 7. Simulated sediment export (ton/day) from different modeling experiments. Percentage changes from Baseline are shown in parentheses.**

GCM	Baseline	LUC		CC		CLUC	
cccma_cgcm3_1	8.5	8.3	(-2.4)	14.7	(72.8)	14.6	(71.1)
cnrm_cm3	7.8	7.7	(-1.0)	12.0	(53.8)	11.4	(46.5)
csiro_mk3_0	8.9	8.9	(-0.7)	14.4	(61.5)	14.1	(57.8)
csiro_mk3_5	9.4	9.2	(-1.7)	12.9	(37.3)	12.7	(35.7)
gfdl_cm2_0	7.1	7.1	(-0.4)	13.1	(84.1)	13.1	(84.4)
giss_model_e_r	8.2	8.0	(-2.2)	9.1	(11.4)	8.4	(3.1)
miub_echo_g	7.8	7.7	(-1.3)	15.2	(96.2)	14.9	(92.4)
mpi_echam5	8.7	8.5	(-1.8)	9.7	(12.2)	12.0	(38.9)
mri_cgcm2_3_2a	8.8	8.7	(-0.4)	14.6	(66.7)	14.2	(61.8)



**Figure 4. Distribution of simulated mean monthly sediment export according to the nine GCMs.**

## CONCLUSIONS AND RECOMMENDATIONS

By the mid-21<sup>st</sup> century, it is projected that the Milwaukee River basin will see a modest growth in urban areas, and a warmer and wetter climate. The confidence level for precipitation increase is not as high as that of temperature increase. Urban areas are projected to expand at the expense of mostly forest and agricultural lands. In response to such projected changes in climate and land use conditions, the following impacts on water resources are projected: (1) mean annual streamflow and sediment export are not influenced much by land use changes; (2) sediment export is projected to increase substantially due to climate change; and (3) low flow indices respond with more sensitivity to climate and land use changes than mean annual streamflow.

The findings suggest that the current pace of urban growth would not pose much threat to the water resources in the area. Therefore, it is recommended that local authorities control the pace of urban growth within the projections presented in this study. Considering that low flow indices responded more easily to climate change than mean streamflow, measures to improve resilience to drought conditions are recommended. In addition, more thorough research on the risk and effect of drought in the Milwaukee River basin is necessary. Finally, with expected increase in sediment export and possibly nutrient export, it would be necessary to reevaluate the total maximum daily load guidelines and take action to reduce soil erosion. The authors also suggest a couple of follow-up research topics that were not included due to constraints in time and resources. First, nutrient transport needs to be included in the impact assessment because nutrient transport is closely tied with sediment export and transport. Second, peak flows need to be investigated in detail because such information may help explain the projected changes in sediment export.

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## APPENDIX A

-List all patents, journal articles, book chapters or books, and other publications resulting from your project, including manuscripts submitted, accepted or in press. Send electronic copies of each publication listed.

Choi, W., F. Pan, and C. Wu, "Impacts of climate change and urban growth on the flow characteristics of the Milwaukee River (Wisconsin, USA)," submitted to *Water Resources Management*  
Deng, Y. and C. Wu, "Development of a Class-based Multiple Endmember Spectral Mixture Analysis (C-MESMA) Approach for Analyzing Urban Environments," *Remote Sensing*, In Press  
Pan, F. and W. Choi, "Effects of Urban Imperviousness Scenarios on Model-Simulated Surface Flow," submitted to *Applied Geography*  
Li, W., C. Wu, and W. Choi, "Predicting future urban impervious surface distribution using cellular automata and regression analysis," submitted to *Journal of Spatial Science*

-List all presentations as complete citations, including title of presentation, date, location, and include approximate number of attendees.

Choi, W., F. Pan, and C. Wu, "Impacts of Climate Change and Urban Growth on the Hydrology of the Milwaukee River Basin, Wisconsin," 2016 Annual Meeting of the American Association of Geographers: San Francisco, California, 1 Apr 2016 (poster, about 10 visitors)  
Li, W. and C. Wu, "A spatial knowledge assisted approach for addressing endmember variability in spectral mixture analysis," Annual Meeting of the American Association of Geographers: San Francisco, California, March 29-April 2, 2016 (30 attendees)  
Wu, C., "Application of spectral mixture analysis in urban remote sensing: problems and potentials," Annual Meeting of the American Association of Geographers: San Francisco, California, March 29-April 2, 2016 (30 attendees)  
Deng, Y. and C. Wu, "Development of a Class-based Multiple Endmember Spectral Mixture Analysis (C-MESMA) Approach for Analyzing Urban Environments," Annual Meeting of the American Association of Geographers: San Francisco, California, March 29-April 2, 2016 (30 attendees)  
Choi, W. and F. Pan, "Impacts of Climate Change on Hydrological Processes and Uncertainties from Climate Models in the Milwaukee River Basin, Wisconsin," 2015 Annual Meeting of the Association of American Geographers: Chicago, Illinois, 23 Apr 2015 (poster, about 5 visitors)  
Pan, F. and W. Choi, "Influence of Different Methods for Estimating Impervious Surface Cover on Model-simulated Streamflow of the Milwaukee River Basin," 2014 Annual Meeting of the Association of American Geographers: Tampa, Florida, 8 Apr 2014 (about 15 attendees)  
Pan, F. and W. Choi, "The Influence of Different Methods for Estimating Impervious Surface Cover on Model-simulated Streamflow of the Milwaukee River Basin," AWRA Wisconsin Section 38th Annual Meeting, Wisconsin Dells, Wisconsin, 13 March 2014 (about 20 attendees)

-List all awards (i.e., best student paper, special project recognition, etc.) related to the project.  
Pan, F., 2014, "Influence of Different Methods for Estimating Impervious Surface Cover on Model-simulated Streamflow of the Milwaukee River Basin," UWM GIS day: Student GIS Project Competition, The Best Student GIS Project for graduate students/GIS certificate student, Second Place

-List the names and contact information for students funded from the grant. If they have graduated and have moved on to a job in science or further study, where are they now?

- Feng PAN (ongoing, Department of Geography, University of Wisconsin-Milwaukee, [fengpan@uwm.edu](mailto:fengpan@uwm.edu))
- Wenliang LI (ongoing, Department of Geography, University of Wisconsin-Milwaukee, [wenliang@uwm.edu](mailto:wenliang@uwm.edu))

-Describe the impact of your work.

- Provide an “elevator speech” (1 paragraph, big picture) to describe in layman terms what you did and why it was important.

It is expected that the Milwaukee River basin will have a warmer and wetter climate by the mid-21<sup>st</sup> century. At the same time, urban growth will continue at a modest pace. How will the water quantity and quality of the Milwaukee River be affected due to these environmental changes? We used a computer program to simulate the water quantity and quality with a range of plausible environmental change scenarios. We used sediment as an indicator of water quality. We found that the quantity and quality of water would not change much with urban growth. On the other hand, climate change was found to have strong impacts, though the level of impacts depended on the global climate models used. At any rate, streamflow and sediment load are more likely to increase than decrease in the future. The study suggests that in order to minimize the impacts on the water resources, it is necessary to keep the pace of urban growth modest and take measures to reduce sediment export to the river.

## Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems

### Basic Information

<b>Title:</b>	Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems
<b>Project Number:</b>	2015WI335B
<b>Start Date:</b>	3/1/2015
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	WI-2nd
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Groundwater, Water Supply, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Matthew GinderVogel, Christina Keenan Remucal

### Publications

There are no publications.

# Report for “Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems”

**Reporting Period:** 3/1/2015 - 2/29/2016

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## **Project**

WR15R009 - Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems

## **Principle Findings and Significance**

Our experiments demonstrate that the poorly crystalline solids collected from the Mn removal system in Madison, WI are capable of oxidizing BPA with a half-life of 2.3 hours (Figure 6). The loss of BPA in the presence of Well 29 Mn(III/IV) oxides was pseudo-first order over 12 hours. As we expected, the reaction rate was 30 times slower than that of  $\delta$ -MnO<sub>2</sub> under the same conditions. However, our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. The solids collected from Well 29 are currently disposed of in a landfill, and therefore serve as an inexpensive oxidant that could be applied in passive drinking water treatment systems to treat urban stormwater or leachate from manure lagoons or landfills.

## **Conclusions/Implications/Recommendations:**

The specific goals of the proposed project are to (1) investigate potential mineral sources of Mn(II) in deep aquifer materials, (2) quantify the mineralogy and dissolution potential of Mn-bearing solids from the Madison Water Utility (MWU) distribution system, and (3) determine the potential of these solids to oxidize organic and inorganic pollutants. A summary of the outcomes for each of these points follows below.

- 1) From our data, sediment from the upper portion of the Mt. Simon aquifer is much richer in Fe and Mn than sediment from deeper portions. The reasons for this variation are not readily apparent from the data collected as part of this project. It is possible that screening wells below the zone of highest sediment Fe and Mn could limit Fe/Mn in the groundwater.
- 2) Unfortunately for our project, but not the residents of Madison, the directional water main flushing implemented by the Madison Water Utility has severely limited solids accumulation in the water distribution system. The limited amount of solid we were able to collect is largely comprised of Fe, Mn, and Al and will likely oxidize organic contaminants. However, as sample size was quite small, we were not able to further characterize these solids.
- 3) Our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. We are currently investigating the ability of the solids collected from the Mn removal to oxidize additional organic and inorganic contaminants.

## **Related Publications:**

**Number of Personnel Involved**

2 Participating faculty/staff  
0 Supported post-docs

**Students Supported**

---

**Name**

Sarah Balgooyen

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

Environmental Chemistry

**Graduation**

6/2019

**Conference Participation**

---

**Title**

American Chemical Society

**Location**

San Diego, CA

**Dates**

Spring 2016

**Number of supported students attending**

1

**Presentations by Students**

Balgooyen, S.; Remucal, C.K.; Ginder-Vogel, M. 2016 Oxidation of Bisphenol A by delta-MnO2. American Chemical Society National Meeting, Spring 2016

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**Title**

Soil Science Society of America Meeting

**Location**

Minneapolis, MN

**Dates**

Fall 2015

**Number of supported students attending**

1

**Presentations by Students**

Balگوoyen, S.; Remucal, C.K.; Ginder-Vogel, M. 2015 Mineral Surface Modification of delta-MnO2 Decreases Bisphenol A Oxidation Rate. Soil Science Society of America Meeting, Minneapolis, MN. Fall 2015 – 50 attendees

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**Title**

Goldschmidt Geochemistry Conference

**Location**

Prague, Czech Republic

**Dates**

Summer 2015

**Presentations by Staff**

Ginder-Vogel, M. 2015 Organic Contaminant Degradation by Mn(IV)oxides, Goldschmidt Geochemistry Conference, Prague, Czech Republic – 50 attendees

---

**Title**

Wisconsin Geologic Survey

**Location**

Madison, WI

**Dates**

Spring 2015

**Presentations by Staff**

Ginder-Vogel, M. 2015 Contaminant Transformation at Transition Metal Oxide Mineral Surfaces, Wisconsin Natural History and Geologic Survey, Madison, WI

---

**Title**

American Chemical Society

**Location**

Denver, CO

**Dates**

Spring 2015

**Presentations by Staff**

Ginder-Vogel, M. 2015 Mechanisms and kinetics of contaminant transformation by Mn(IV) oxides. American Chemical Society National Meeting, Denver, CO. Spring 2015 - 100 attendees

Journal Articles and Other Publications

Title

Balگووین, S.; Remucal, C.K.; Ginder-Vogel, M. Oxidation of Bisphenol A by delta-MnO2. In preparation for Environmental Science and Technology

Type of Publication

Book or Monograph (Peer-reviewed)

Title

Balگووین, S.; Remucal, C.K.; Ginder-Vogel, M. Characterization of Solid and Aqueous Products of Bisphenol-A Degradation by delta MnO2. In preparation for Journal of Visual Experiments

Type of Publication

Book or Monograph (Peer-reviewed)

Awards and Achievements

Title

National Science Foundation Graduate Research Fellowship

Recipient(s)

Sara Balگووین

Awarded By

National Science Foundation

Type of Award

Research

Student Award?

Yes

Number of students receiving award

1

Research Patent or Copyright

No research patents or copyrights reported.

Completion Summary

Conclusions and Recommendations:

The specific goals of the proposed project are to (1) investigate potential mineral sources of Mn(II) in deep aquifer materials, (2) quantify the mineralogy and dissolution potential of Mn-bearing solids from the Madison Water Utility (MWU) distribution system, and (3) determine the potential of these solids to oxidize organic and inorganic

pollutants. A summary of the outcomes for each of these points follows below.

- 1) From our data, sediment from the upper portion of the Mt. Simon aquifer is much richer in Fe and Mn than sediment from deeper portions. The reasons for this variation are not readily apparent from the data collected as part of this project. It is possible that Fe/Mn in the groundwater could be limited by screening wells below the zone of highest Fe and Mn.
- 2) Unfortunately for our project, but not the residents of Madison, the directional water main flushing implemented by the Madison Water Utility has severely limited solids accumulation in the water distribution system. The limited amount of solid we were able to collect is largely comprised of Fe, Mn, and Al and will likely oxidize organic contaminants. However, as sample size was quite small, we were not able to further characterize these solids.
- 3) Our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. We are currently investigating the ability of the solids collected from the Mn removal to oxidize additional organic and inorganic contaminants.

Final Report for “Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in  
Municipal Water Systems”

PI: Matthew Ginder-Vogel – University of Wisconsin – Madison

Co-PI: Christina Remucal – University of Wisconsin - Madison

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## Project Summary

Title: Effect of Source Chemistry on Mn-Bearing Solid Dissolution and Reactivity in Municipal Water Systems

Project I.D.: WR15R009

### Investigators:

Principle Investigator: Matthew Ginder-Vogel, Assistant Professor, Dept. of Civil and Environmental Engineering, University of Wisconsin – Madison

Co-Principle Investigator: Christina Remucal, Assistant Professor, Dept. of Civil and Environmental Engineering, University of Wisconsin – Madison

Research Assistant: Sarah Balgooyen, Doctoral Candidate, Environmental Chemistry and Technology Program, University of Wisconsin – Madison

Period of Contract: March 1, 2015, through February 29, 2016

### Background/Need:

Flushing of sediments from the water mains may result in elevated manganese (Mn) concentrations in the drinking water distribution system. For example, during 2006, 17 of 1,119 sampled properties in Madison, WI had Mn levels that exceeded the lifetime health advisory value of 300 µg/L.<sup>1</sup> In response to public concerns, the City of Madison conducted extensive testing of the wellheads and found that only four of the 24 wells produced water near or above the Secondary Maximum Contaminant Level.<sup>2, 3</sup> The city initiated uni-directional flushing of the water mains and installed a treatment facility at Well 29, which had Mn levels of 124 µg/L.<sup>1</sup> These approaches have been largely successful at limiting Mn concentrations in drinking water, yet the Mt. Simon aquifer continues to be a long-term source of dissolved manganese in municipal water systems Madison and throughout southern Wisconsin. Additionally, fundamental information concerning the solubility and reactivity of Mn-bearing solid phases in municipal water distribution systems remains sparse. The proposed research project is designed to address this gap in knowledge by developing a quantitative relationship between source chemistry and Mn-bearing solid dissolution potential and reactivity.

### Objectives:

**Objective 1. Identify Mn bearing minerals in Mt. Simon Aquifer materials.**

**Objective 2. Quantify mineralogy and dissolution potential of Mn-bearing solids**

**Objective 3. Determine oxidative reactivity of Mn-bearing solids.**

### Methods:

In order to achieve the objectives described above, we examined Mn chemistry from its potential sources in the Mt. Simon Aquifer to its ultimate fate as oxidized solids in the MWU distribution system. Initially, we identified potential dissolved Mn sources in cuttings from the Mt. Simon Aquifer by utilizing wet chemical (e.g., extractions) techniques. We then collected oxidized Mn-bearing solids from the MWU distribution system and characterized the reactivity of these phases by reaction with organic contaminants.

We worked with the Wisconsin Geological and Natural History Survey to collect fresh sediment samples from Mt. Simon Formation. Additionally, we collected solid samples from the Madison water distribution system during water main flushing during the summer of 2014 and the Well 29 Mn removal system during the summers of 2014 and 2105.

## Results and Discussion:

Our experiments demonstrate that the poorly crystalline solids collected from the Mn removal system in Madison, WI are capable of oxidizing BPA with a half-life of 2.3 hours (Figure 6). The loss of BPA in the presence of Well 29 Mn(III/IV) oxides was pseudo-first order over 12 hours. As we expected, the reaction rate was 30 times slower than that of  $\delta$ -MnO<sub>2</sub> under the same conditions. However, our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. The solids collected from Well 29 are currently disposed of in a landfill, and therefore serve as an inexpensive oxidant that could be applied in passive drinking water treatment systems to treat urban stormwater or leachate from manure lagoons or landfills.

## Conclusions/Implications/Recommendations:

The specific goals of the proposed project are to (1) investigate potential mineral sources of Mn(II) in deep aquifer materials, (2) quantify the mineralogy and dissolution potential of Mn-bearing solids from the Madison Water Utility (MWU) distribution system, and (3) determine the potential of these solids to oxidize organic and inorganic pollutants. A summary of the outcomes for each of these points follows below.

- 1) From our data, sediment from the upper portion of the Mt. Simon aquifer is much richer in Fe and Mn than sediment from deeper portions. The reasons for this variation are not readily apparent from the data collected as part of this project. It is possible that screening wells below the zone of highest sediment Fe and Mn could limit Fe/Mn in the groundwater.
- 2) Unfortunately for our project, but not the residents of Madison, the directional water main flushing implemented by the Madison Water Utility has severely limited solids accumulation in the water distribution system. The limited amount of solid we were able to collect is largely comprised of Fe, Mn, and Al and will likely oxidize organic contaminants. However, as sample size was quite small, we were not able to further characterize these solids.
- 3) Our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. We are currently investigating the ability of the solids collected from the Mn removal to oxidize additional organic and inorganic contaminants.

## Related Publications:

Balگوoyen, S.; Remucal, C.K.; Ginder-Vogel, M. Oxidation of Bisphenol A by delta-MnO<sub>2</sub>. In preparation for *Environmental Science and Technology*

Balگوoyen, S.; Remucal, C.K.; Ginder-Vogel, M. Characterization of Solid and Aqueous Products of Bisphenol-A Degradation by delta MnO<sub>2</sub>. In preparation for *Journal of Visual Experiments*

Key Words: Groundwater, BPA, Manganese Oxides,

Funding: University of Wisconsin System

## Introduction:

**Manganese in drinking water.** Manganese (Mn) is ubiquitous in air, soil, and water and is considered to be an essential nutrient for humans and animals. Although manganese is an essential nutrient at low doses, chronic exposure to high doses may potentially lead to neurological effects. As a result, the US Environmental Protection Agency (EPA) recommends a lifetime health advisory value of 300  $\mu\text{g/L}$  for healthy adults. Ten-day advisory levels of 300 and 1,000  $\mu\text{g/L}$  are recommended for infants younger than six months and for healthy adults, respectively. In order to address consumer complaints about staining and taste issues, the EPA established a Secondary Maximum Contaminant Level (SMCL) of 50  $\mu\text{g/L}$  for Mn in drinking water in 2004.<sup>1</sup> The health advisories and SMCL are not federally enforceable regulations and are intended as guidelines for the States.<sup>1</sup>

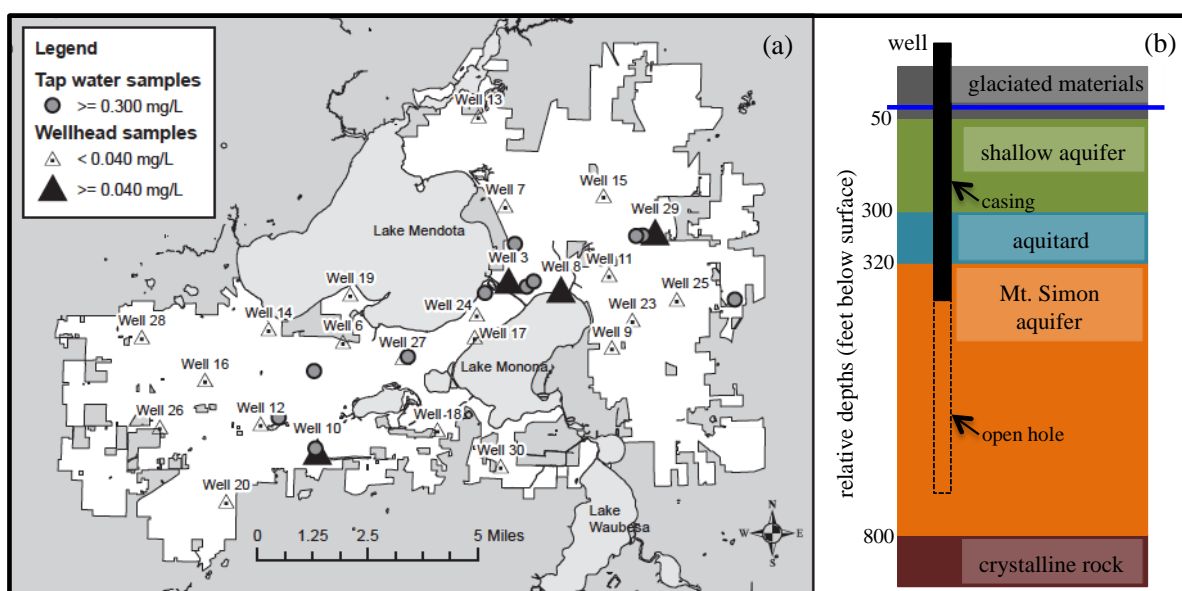
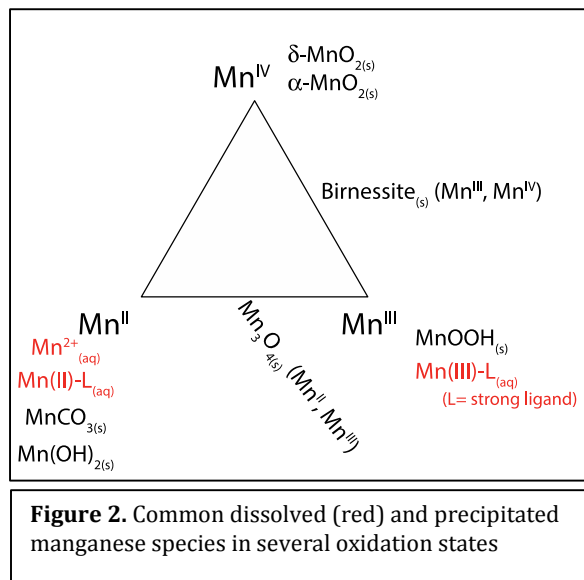


Figure 1. (a) Wells by Mn concentration and tap water samples with excess Mn in Madison, Wisconsin (after Schlenker) and (b) typical construction of Madison high capacity wells.

Flushing of sediments from the water mains may result in elevated Mn concentrations in the distribution system. During 2006, 17 of 1,119 sampled properties in Madison, WI had Mn levels that exceeded the lifetime health advisory value.<sup>2</sup> In response to public concerns, the City of Madison conducted extensive testing of the wellheads and found that only four of the 24 wells produced water near or above the SMCL (Figure 1). The city initiated uni-directional flushing of the water mains and installed a treatment facility at Well 29, which had Mn levels of 124  $\mu\text{g/L}$ . These approaches have been largely successful at limiting Mn concentrations in drinking water, yet the Mt. Simon Aquifer continues to be a long-term source of Mn. Additionally, fundamental information concerning the solubility and reactivity of Mn-bearing solid phases in MWU's distribution systems remains sparse. **Our research project addresses this gap in knowledge by developing a quantitative relationship between source chemistry and Mn-bearing solid dissolution potential and reactivity.** The objectives of this proposal are to (1) identify Mn-bearing solid phases from well cuttings obtained from the Mt. Simon aquifer and (2) characterize

the dissolution potential and (3) the reactivity of Mn-bearing solid-phases formed in MWU's water distribution system and Mn removal system located at MWU's well 29.



### Mechanisms of Mn oxide formation.

Manganese is the third most abundant transition metal in the Earth's crust ( $9.5 \times 10^2$  ppm, respectively).<sup>3</sup> The precipitation and dissolution of and Mn-bearing solid phases is strongly influenced by reduction and oxidation (redox) chemistry (Figure 2).<sup>4</sup> Significant concentrations of dissolved Mn(II) in natural waters generally only occur in the absence of oxygen ( $O_2$ ). In the presence of  $O_2$  insoluble Mn(III/IV) oxides form and limit the dissolved concentration of Mn.

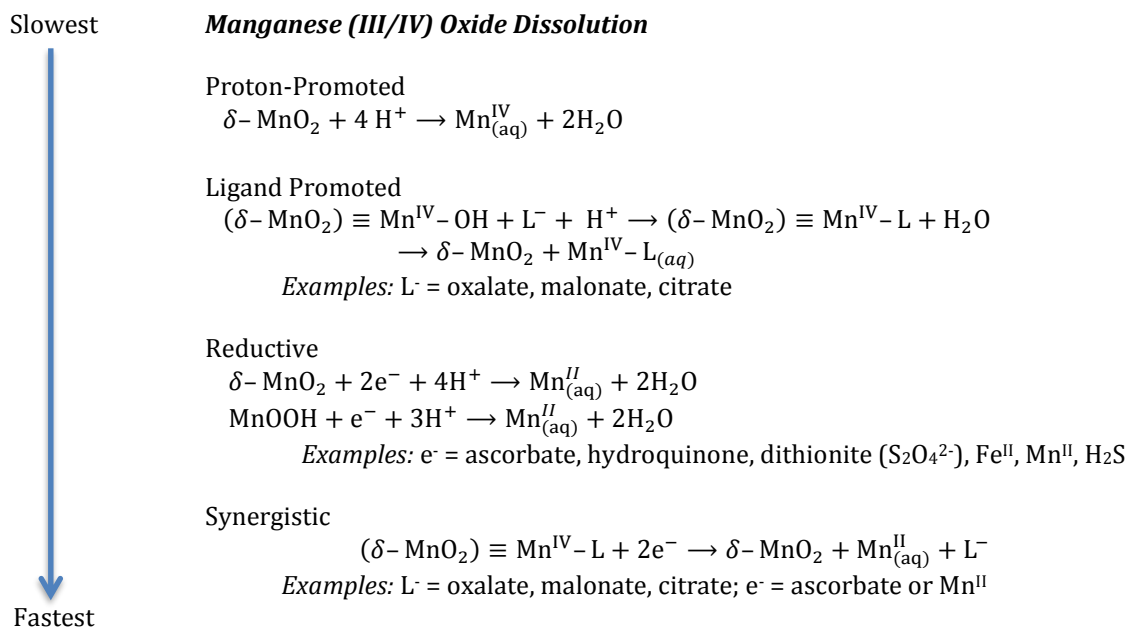
Although the interconversion among redox and physical states is thermodynamically favorable in many environmental settings, it is generally kinetically limited in the absence of catalysis. For example, oxidation of aqueous Mn(II) by  $O_2$  is thermodynamically favorable at pH 8.4, yet the

reaction proceeds across years in the absence of catalysts.<sup>5</sup> The rate and pathway of Mn(II) oxidation and precipitation is influenced by a variety of factors including ligands, foreign surfaces, surface-active ions, and pH. Similarly, dissolution of Mn(III/IV) solids exposed to undersaturated conditions is a thermodynamically favorable, but the uncatalyzed rates are exceedingly slow.<sup>6</sup>

Once formed, **Mn-oxides are considered to be the strongest, naturally occurring oxidants** and oxidize a large variety of organic and inorganic substrates, as described in more detail below. In addition, the mobility and bioavailability of environmental contaminants, such as heavy metals and toxic organic molecules, are strongly regulated by manganese oxides. Precipitation of Mn oxide minerals in municipal water distribution systems may serve as a reservoir of Mn. The Mn may be released back into solution through dissolution due to changing geochemical conditions (e.g., flushing of water mains). Mn oxide mineral dissolution will also release any bound heavy metal contaminants into solution.

**Mn oxide dissolution mechanisms.** Dissolution rates of Mn oxide solids are dependent on many factors including surface area, pH and ligand concentration. For example, dissolution rates increase under acidic conditions. The rates of the parallel dissolution pathways vary over several orders of magnitude (Figure 3). The dissolution pathways include, from slowest to fastest, proton-promoted, ligand-promoted, reductive, and synergistic (Figure 3). Further, the rates depend on the crystallinity and degree of Fe(III) substitution of the Mn oxide minerals.<sup>5</sup> For example, nanocrystalline Mn(IV) $O_2$  ( $\delta$ -Mn $O_2$ ) dissolves at least 10 times faster than birnessite, its more crystalline equivalent.<sup>7</sup> Dissolution rates are also temporally dependent and often pass through periods of rapid dissolution, which are at least 10 times faster than steady state dissolution rates, after minor geochemical changes (e.g., change in pH, introduction of reducing agents and/or ligands).<sup>4</sup> Thus, in order to understand processes controlling the dissolution of Mn bearing minerals in the MWU supply system it is essential to develop an

understanding of their chemical composition, crystallinity, and susceptibility to the four dissolution mechanisms described in Figure 3.



**Figure 3.** Stoichiometry and relative dissolution rates of proton promoted, ligand-promoted, reductive, and synergistic pathways of Mn(III/IV) oxide dissolution. Photoreductive pathways are omitted.

## Procedures and Methods:



**Figure 4.** Collection of Mn oxide slurry from Well 29 Mn removal system.

In order to achieve the objectives described above, we examined Mn chemistry from its potential sources in the Mt. Simon Aquifer to its ultimate fate as oxidized solids in the MWU distribution system. Initially, we identified potential dissolved Mn sources in cuttings from the Mt. Simon Aquifer by utilizing wet chemical (e.g., extractions) techniques. We then collected oxidized Mn-bearing solids from the MWU distribution system and characterized the reactivity of these phases by reaction with organic contaminants.

We worked with the Wisconsin Geological and Natural History Survey to collect fresh sediment samples from Mt. Simon

Formation. Additionally, we collected solid samples from the Madison water distribution system during water main flushing during the summer of 2014 and the Well 29 Mn removal system

during the summers of 2014 and 2105 (Figure 4).

#### *Solid-Phase Characterization*

X-ray diffraction patterns were collected using a Rigaku D/Max Rapid II diffractometer equipped with a Mo X-ray tube, operating at 50 kV and 50 mA. Dried solids were prepared in sealed silica capillary tubes.

Solid-phase elemental composition was determined by complete dissolution of all collected solids in concentrated hydrochloric acid and analysis of Fe and Mn content via inductively coupled plasmas – optical emission spectrometry (ICP-OES).

#### *Reactivity with organic contaminants*

The ability of solids collected from the Well 29 Mn removal system to oxidize organic contaminants was investigated by reaction of a solution containing 80  $\mu$ M BPA to 0.33 g/L filter solid. The pH of the solution was buffered at 7. The reaction was sampled at regular intervals and analyzed to determine the concentration of dissolve Mn and BPA in solution at each time point. BPA concentration was determined using high performance liquid chromatography (HPLC) and dissolved Mn concentration was determined using ICP-OES.

### **Results and Discussion:**

#### *Aquifer Material Characterization*

Table 1: Total manganese and iron (micrograms/gram sediment) measured in aquifer materials collected from wells drilled in Dane County.

<b>Well Location</b>	<b>Interval (feet BGS)</b>	<b>Mn (ug/g)</b>	<b>±</b>	<b>Fe (ug/g)</b>	<b>±</b>
Madison, WI	185-230	221.8	12.5	1896	118
Madison, WI	230-275	112.8	6.5	2385	150
Madison, WI	310-315	126.2	7.3	3671	230
Madison, WI	325-350	149.8	8.3	2636	165
Madison, WI	350-370	73.0	4.2	592	38
Madison, WI	370-418	12.2	0.7	162	13
Verona, WI	260-300	853.4	47.1	4408	287
Verona, WI	380-385	162.2	9.0	1432	91
Verona, WI	430-435	8.5	0.6	194	13
Verona, WI	750-760	6.1	0.5	254	16
Verona, WI	950-960	7.9	0.5	800	50
Verona, WI	1160	130.0	7.3	9794	613

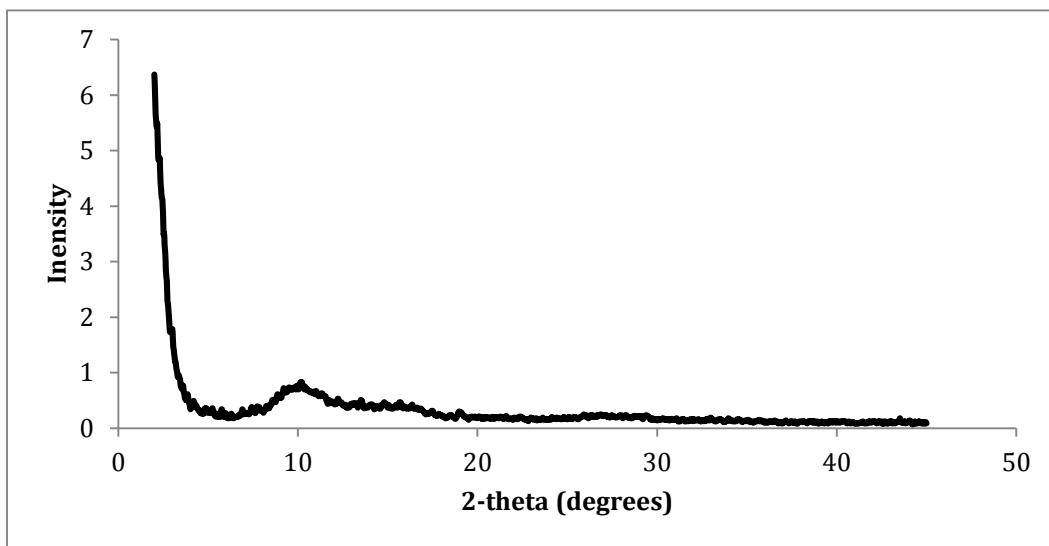
Total iron and manganese vary greatly as a function of depth in Mount Simon aquifer materials collected from wells bored in Madison and Verona, Wisconsin (Table 1). Generally, the concentration of Fe and Mn decreases with depth. Additionally, the concentration of Fe and Mn is much higher in the sediments obtained from the Verona, WI well. The exact reasons for this trend are not clear; however, it's clear that to avoid the highest concentration of Mn and Fe, wells should be screened deeper in the Mt. Simon Aquifer.

#### *Madison Water Utility (MWU) Water Distribution Sediments*

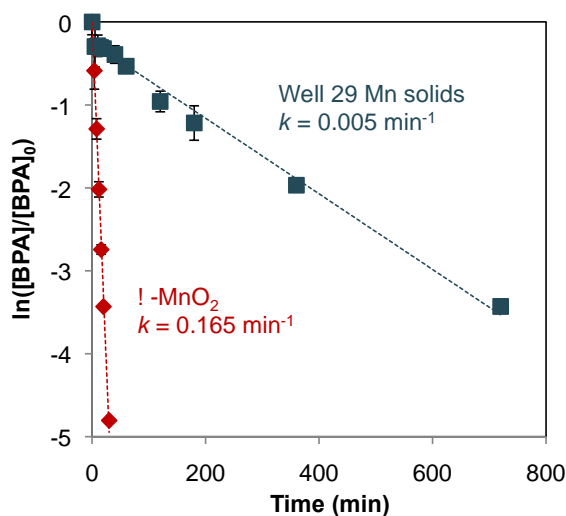
Solids collected during water main flushing operations over the summer of 2014 are predominantly composed of iron, manganese, and aluminum, with iron being the most abundant element and aluminum being the least abundant (data not shown). Unfortunately, we were not able to collect enough of these solids for further characterization of their reactivity with respect to organic contaminants.

#### *Solids from MWU Well 29 Mn Removal System*

Solids collected from the Mn removal system located at Well #29 (Figure 1) in Madison, WI (Figure 4) are composed of ~42% Fe and 8% Mn. X-ray diffraction analysis of the solids reveals that the solid-phase is X-ray amorphous, with no crystalline phases detected (Figure 5). This basic geochemical characterization indicates that the solids from this facility are candidates for reuse in organic contaminant removal systems.



**Figure 5.** X-ray diffraction pattern of Fe/Mn oxide solids collected well # 29 Mn removal system in Madison, WI. Note the lack of distinct peaks in the pattern indicating that there are no crystalline mineral phases present in this sample.



**Figure 6.** Degradation of 5 µM BPA by δ-MnO<sub>2</sub> and solids isolated from Well 29 (8.5% Mn by mass) at pH 5. The initial concentration of both solids was 400 µM as Mn.

Our experiments demonstrate that *the poorly crystalline solids collected from the Mn removal system in Madison, WI are capable of oxidizing BPA* with a half-life of 2.3 hours (Figure 6). The loss of BPA in the presence of Well 29 Mn(III/IV) oxides was pseudo-first order over 12 hours. As we expected, the reaction rate was 30 times slower than that of δ-MnO<sub>2</sub> under the same conditions. However, our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. The solids collected from Well 29 are currently disposed of in a landfill, and therefore serve as an inexpensive oxidant that could be applied in passive drinking water treatment systems to treat urban stormwater or leachate from manure lagoons or landfills.

## Conclusions and Recommendations:

The specific goals of the proposed project are to (1) investigate potential mineral sources of Mn(II) in deep aquifer materials, (2) quantify the mineralogy and dissolution potential of Mn-bearing solids from the Madison Water Utility (MWU) distribution system, and (3) determine the potential of these solids to oxidize organic and inorganic pollutants. A summary of the outcomes for each of these points follows below.

- 1) From our data, sediment from the upper portion of the Mt. Simon aquifer is much richer in Fe and Mn than sediment from deeper portions. The reasons for this variation are not readily apparent from the data collected as part of this project. It is possible that Fe/Mn in the groundwater could be limited by screening wells below the zone of highest Fe and Mn.
- 2) Unfortunately for our project, but not the residents of Madison, the directional water main flushing implemented by the Madison Water Utility has severely limited solids accumulation in the water distribution system. The limited amount of solid we were able to collect is largely

comprised of Fe, Mn, and Al and will likely oxidize organic contaminants. However, as sample size was quite small, we were not able to further characterize these solids.

3) Our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. We are currently investigating the ability of the solids collected from the Mn removal to oxidize additional organic and inorganic contaminants.

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1. Agency, U. S. E. P. *Drinking water health advisory for manganese*; 2004.
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6. Diem, D.; Stumm, W., Is dissolved  $\text{Mn}^{2+}$  being oxidized by  $\text{O}_2$  in absence of Mn-bacteria or surface catalysts? *Geochim. Cosmochim. Acta* **1984**, 48, 1571-1573.
7. Stumm, W., Reactivity at the mineral-water interface: dissolution and inhibition. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **1997**, 120, 143-166.

## Appendix A: Awards, Publications, Reports, Patents, Presentations, Students, Impact

### Publications, Reports and Patents:

v

### Presentations:

Balگوoyen, S.; Remucal, C.K.; Ginder-Vogel, M. 2016 Oxidation of Bisphenol A by delta-MnO<sub>2</sub>. American Chemical Society National Meeting, Spring 2016 – 50 attendees

Balگوoyen, S.; Remucal, C.K.; Ginder-Vogel, M. 2015 Mineral Surface Modification of delta-MnO<sub>2</sub> Decreases Bisphenol A Oxidation Rate. Soil Science Society of America Meeting, Minneapolis, MN. Fall 2015 – 50 attendees

Ginder-Vogel, M. 2015 Organic Contaminant Degradation by Mn(IV)oxides, Goldschmidt Geochemistry Conference, Prague, Czech Republic – 50 attendees

Ginder-Vogel, M. 2015 Contaminant Transformation at Transition Metal Oxide Mineral Surfaces, Wisconsin Natural History and Geologic Survey, Madison, WI - 10 attendees

Ginder-Vogel, M. 2015 Mechanisms and kinetics of contaminant transformation by Mn(IV) oxides. American Chemical Society National Meeting, Denver, CO. Spring 2015 - 100 attendees

### Awards:

The initial results of this research were leveraged to write a successful proposal to the National Science Foundation to continue these studies.

### Students:

Sarah Balگوoyen – Doctoral Candidate in the Environmental Chemistry and Technology program at UW Madison  
balگوoyen@wisc.edu, 660 N. Park St., Madison, WI 53706

### Impact of Work:

Our experiments demonstrate that *the poorly crystalline solids collected from the Mn removal system in Madison, WI are capable of oxidizing BPA* with a half-life of 2.3 hours (Figure 6). The loss of BPA in the presence of Well 29 Mn(III/IV) oxides was pseudo-first order over 12 hours. As we expected, the reaction rate was 30 times slower than that of  $\delta$ -MnO<sub>2</sub> under the same conditions. However, our data demonstrates that the ability of the environmentally relevant Mn oxides to oxidize a range of target contaminants warrants further investigation. The solids collected from Well 29 are currently disposed of in a landfill, and therefore serve as an inexpensive oxidant that could be applied in passive drinking water treatment systems to treat urban stormwater or leachate from manure lagoons or landfills.



# Direction of Peer Review and Selection Panel Activities for FY 2015 U.S. Geological Survey – National Institutes for Water Resources National Competitive Grants Program

## Basic Information

<b>Title:</b>	Direction of Peer Review and Selection Panel Activities for FY 2015 U.S. Geological Survey – National Institutes for Water Resources National Competitive Grants Program
<b>Project Number:</b>	2015WI358S
<b>USGS Grant Number:</b>	
<b>Sponsoring Agency:</b>	U.S. Geological Survey
<b>Start Date:</b>	3/6/2015
<b>End Date:</b>	9/30/2015
<b>Funding Source:</b>	104S
<b>Congressional District:</b>	
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	None, None, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	James Hurley

## Publications

There are no publications.

# WR15R010: Direction of Peer Review and Selection Panel Activities for FY 2015 U.S. Geological Survey ; National Institutes for Water Resources National Competitive Grants Program

**Reporting Period:** 7/1/2015 - 6/30/2016

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## **Project**

WR15R010 - Direction of Peer Review and Selection Panel Activities for FY 2015 U.S. Geological Survey ; National Institutes for Water Resources National Competitive Grants Program

## **Principle Findings and Significance**

FY2015 104G National Competition Summary

- The niwr.net site opened November 2014 to accept proposals. The deadline for submission was February 19, 2015 with institute approval due by March 12, 2015.
- One hundred and one proposals were received, approved by state institutes and by USGS. Seven additional proposals did not follow proper submission/approval processes and were not allowed to be considered in the competition.
- The entire review process conducted online through niwr.net. Requests for reviews were to 1,204 potential reviewers. A total of 391 individuals agreed to participate in the review. A total of 442 individuals declined. Even after reminders, 286 individuals did not reply. There were 83 entries in the database that were undeliverable and needed updates.
- A total of 356 reviews were submitted, representing a 91% return by committed reviewers. A minimum of three reviews were received for each of the 101 proposals and no reviewer was asked to review more than one proposal.
- The qualitative assessment score was converted to a numerical rating for each review by the following: Outstanding – 4 points; Excellent – 3 points; Good – 2 points; Adequate – 1 point; Do Not Fund – 0 points. Proposals with an average score of 3.00 or better were forwarded to the panel. Panelists were allowed to bring any other proposal forward.
- A total of 32 proposals were forwarded to the panel, which met in Madison, Wisconsin July 28-29, 2016. Four proposals were chosen for funding.

## **Number of Personnel Involved**

1 Participating faculty/staff

0 Supported post-docs

**Students Supported**

No students reported.

**Conference Participation**

No conferences reported.

**Journal Articles and Other Publications**

No journal articles and other publications reported.

**Awards and Achievements**

No awards and achievements reported.

**Research Patent or Copyright**

No research patents or copyrights reported.

**Completion Summary**

This project is complete and marks Hurley's completion of 13 years leading the peer review and panel efforts for the NIWR USGS 104G National Competition. The competition in 2015 led to fully funding four projects:

- 2015SC101G - Human and Ecological Health Impacts Associated with Water Reuse: Engineered Systems for Removing Priority Emerging Contaminants (South Carolina - \$250,000 federal funds)
- 2015SD248G - Hydrologic Life Cycle Impact of Mountain Pine Bark Beetle Infestations (South Dakota - \$250,000 federal funds)
- 2015CO316G - Trace Organic Contaminants (TOrcs) in Urban Stormwater and Performance of Urban Bioretention Systems: a Field and Modeling Study (Colorado - \$249,960 federal funds)
- 2015IL298G - Using bioavailability to assess pyrethroid insecticide toxicity in urban sediments (Illinois - \$249,329 federal funds)

Upon completion of the review, the Kansas Water Resources Institute will assume the duties for the 104G competition.

# Evaluating the Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings

## Basic Information

<b>Title:</b>	Evaluating the Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings
<b>Project Number:</b>	2015WI359S
<b>USGS Grant Number:</b>	
<b>Sponsoring Agency:</b>	Nuclear Regulatory Commission
<b>Start Date:</b>	1/27/2015
<b>End Date:</b>	11/16/2017
<b>Funding Source:</b>	104S
<b>Congressional District:</b>	
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	None, None, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Craig H Benson

## Publications

There are no publications.

# Project Number: WR15R008 Title: Evaluating the Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings

**Reporting Period:** 7/1/2015 - 6/30/2016

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## **Project**

WR15R008 - Evaluating the Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings

## **Principle Findings and Significance**

Background: Disposal facilities for uranium mill tailings generated by current and historic uranium beneficiation operations have been constructed at locations throughout the United States as required by the Uranium Mine Tailings Radiation Control Act (UMTRCA). Nearly all UMTRCA facilities rely on a surface cover to control the rate at which contaminants migrate in the gas and water phases from the tailings and into the surrounding environment. Understanding the significance of macrostructure induced by abiotic and biotic processes in cover soils, how the structure varies with depth, and the impact of structure on emissions of radon and water containing ground water contaminants, is critical to understanding surface barrier strategies and for designing future surface barriers. Although the mechanisms and impacts associated with these structure-forming processes have been established, their significance in terms of water and gas transport into and out of uranium mill tailings disposal facilities is not known.

Project Objectives: This study is evaluating the effects of soil structure formation on the hydraulic conductivity and gaseous diffusivity of Rn barriers, how structural development varies with depth and thickness of the Rn barrier, and how structure influences transmission of radon and seepage carrying ground water contaminants.

Activities and Findings during Reporting Period:

- 1) Field site selection: Two UMTRCA surface barriers under surveillance by Department of Energy Legacy Management (LM) were selected for field monitoring and evaluation. Sites were selected based on analysis of barrier age, depth, and thickness in locations representing a range of vegetation and climates. Field work at these two sites took place in April 2016 and June 2016. Two additional sites will be selected for field work as part of ongoing efforts.
- 2) Sensor calibration: Alternative measurement techniques for measuring radon flux in the field were examined through a literature review. Two sensor types were identified for field testing: activated carbon (AC) canisters and an electronic radon detection system (RAD7). A suite of laboratory tests was conducted to develop protocols for field measurements and to characterize variables that affect the measurements, including relative humidity, sensing chamber size, and exposure duration. Significant and consistent differences were observed between radon

concentrations measured using the RAD7 and concentrations measured using AC. The ratio of measured concentrations averaged 0.58, meaning AC canisters measured 42.0% less radon than the RAD7. A journal publication summarizing results from this suite of tests is in preparation.

3) Laboratory Diffusion Apparatus: A laboratory apparatus was developed for measuring effective radon diffusion coefficients of compacted clay specimens subjected to wet-dry cycles. Objectives are to quantify the effects of soil structure development on gaseous radon diffusion coefficient. Preliminary tests were conducted using six clays with varying plasticity compacted at moisture and density conditions representing initial placement conditions common of compacted clay cover systems. A journal publication summarizing results from this suite of tests is in preparation.

**Number of Personnel Involved**

- 5 Participating faculty/staff
- 1 Supported post-docs

**Students Supported**

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**Name**

Hyunjun Oh

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

CEE

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**Name**

Nick Stefani

**Affiliation**

University of Wisconsin-Madison

**Degree**

MA/MS

**Major/Specialization**

GLE

**Graduation**

8/2016

**Thesis Title**

Field and Laboratory Measurement of Radon Flux and Diffusion for Uranium Mill Tailings Cover Systems

**Job Placement**

Consulting

---

**Name**  
Joel Krech

**Affiliation**  
University of Wisconsin-Madison

**Degree**  
BA/BS

**Major/Specialization**  
GLE

**Graduation**  
12/2015

**Job Placement**  
Consulting

---

**Name**  
Samuel Wilson

**Affiliation**  
University of Wisconsin-Madison

**Degree**  
BA/BS

**Major/Specialization**  
GLE

**Graduation**  
12/2015

**Job Placement**  
Consulting

---

**Name**  
Kahao Lim

**Affiliation**  
Other

**Degree**  
BA/BS

**Major/Specialization**  
CEE

**Graduation**  
5/2016

**Job Placement**  
Other

Conference Participation

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Title

GeoChicago 2016: Sustainability, Energy, and the Geoenvironment

Location

Chicago, IL

Dates

August 14-17, 2016

Number of supported students attending

1

Presentations by Students

Stefani, N., Likos, W.J., and Benson, C.H., 2016, "Evaluation of two methods for measuring radon flux from earthen radon barriers," Proc. GeoChicago 2016: Sustainability, Energy, and the Geoenvironment, Chicago, IL.

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Title

UW-Madison College of Engineering, Undergraduate Research Forum

Location

UW-Madison

Dates

Spring 2015

Number of supported students attending

2

Presentations by Students

Krech, J., Stefani, N., Likos, W.J. (poster); EVALUATING THE EFFECTIVENESS OF SURFACE COVERS FOR CONTROLLING FLUXES OF WATER AND RADON AT DISPOSAL FACILITIES FOR URANIUM MILL TAILINGS

Journal Articles and Other Publications

No journal articles and other publications reported.

Awards and Achievements

No awards and achievements reported.

Research Patent or Copyright

No research patents or copyrights reported.

# Application of Mercury Isotopes to Inform Ecosystem Restoration in the Great Lakes Region

## Basic Information

<b>Title:</b>	Application of Mercury Isotopes to Inform Ecosystem Restoration in the Great Lakes Region
<b>Project Number:</b>	2015WI360S
<b>USGS Grant Number:</b>	
<b>Sponsoring Agency:</b>	U.S. Geological Survey
<b>Start Date:</b>	7/10/2015
<b>End Date:</b>	2/28/2017
<b>Funding Source:</b>	104S
<b>Congressional District:</b>	
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	None, None, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	James Hurley

## Publications

There are no publications.

# Application of Mercury Isotopes to Inform Ecosystem Restoration in the Great Lakes Region

**Reporting Period:** 3/1/2015 - 2/29/2016

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## Project

WR15R011 - Application of Mercury Isotopes to Inform Ecosystem Restoration in the Great Lakes Region

## Principle Findings and Significance

The specific tasks of this research and progress to reach these goals are:

1. Apply the MC ICP-MS fingerprinting methodology to provide quantitative estimates of which Hg sources (atmospheric, terrestrial runoff, and legacy point source) are driving current fish Hg levels at these two river mouth ecosystem settings;

Our results were focused mainly on the Fox River, Wisconsin for the first phase of the study. Results indicated relative to baseline, enhanced Hg sediment deposition began in the 1890s in Green Bay and was evident in the early 1800's in offshore Lake Michigan. Isotopic signatures allowed for the utilization of a binary mixing model reliant on HgT concentration and  $\delta^{202}\text{Hg}$  values (Yin et al. 2016). Model output confirmed that the contamination evident in Green Bay is most likely due to local sources that are mainly constrained to Green Bay whereas offshore elevations in HgT concentrations are more likely the result of increased Hg in the global pool. This study also showed an increase in odd isotope mass independent fractionation (MIF) from within Green Bay to offshore Lake Michigan. Greater positive odd MIF is likely indicative of both enhanced photoreduction in offshore regions as well as proportionally more atmospherically-derived Hg and proportionally less watershed-derived Hg in the offshore region. This is consistent with data from our comparative Great lakes sediment study (Lepak et al. 2015).

A preliminary food web investigation of the Fox River was also conducted. For the study, baitfish (Emerald Shiner and Gizzard Shad), benthivores (Redhorse Sucker), and piscivorous fish (Walleye and Smallmouth Bass) were electroshocked in three locations along the Fox River: below the Little Rapids Dam, below the De Pere Dam and just outside the harbor walls in Green Bay.

Isotopic Hg signatures in fish of these regions were compared to surface sediment from a nearby site in Green Bay to help determine whether Hg found in the food web resembled legacy Hg in Green Bay. As fish contain primarily methylmercury, sediment Hg speciation is typically dominated by inorganic Hg. The processes that convert a portion of an Hg pool from inorganic to the methylmercury found in fish (methylation, demethylation, photochemical reduction and photochemical demethylation) are highly complex and may result in Hg fractionation, mass-dependent and mass-independent, prior to organism uptake. For this reason, Hg isotope signatures found in biota may not be directly comparable to the legacy Hg found in the sediment.

2. Develop a generalized conceptual model that will aid resource managers and restoration decision makers in the most effective means to reduce fish mercury levels at these two sites, and similar settings.

We have developed a triple mixing model to assess sources to sediments of the overall Great Lakes (Lepak et al. 2015). Similarly, Yin et al. (2016) used this approach to assess sources to Green Bay sediments. We plan to expand our modeling to include bioaccumulation and effects of Hg isotopic distribution through collaborative work on both river systems.

Our work in the second phase of this study will be focused primarily on the St. Louis River Estuary.

**Number of Personnel Involved**

- 1 Participating faculty/staff
- 1 Supported post-docs

**Students Supported**

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**Name**

Ryan Lepak

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

Environmental Chemistry

**Graduation**

12/2018

**Thesis Title**

TBD

**Conference Participation**

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**Title**

Twelfth International Conference on Mercury as a Global Pollutant.

**Location**

Jeju, Korea

**Dates**

June 2015

**Number of supported students attending**

1

**Presentations by Staff**

Hurley, J., R. Lepak, R. Yin, D. Krabbenhoft, J. DeWild, J. Ogorek, C. Thompson, M.Tate, M. Maglio. 2015. Mercury Sources to Sediments of the Great Lakes: Insights from Stable Isotope Analyses. Twelfth International Conference on Mercury as a Global Pollutant. Jeju, Korea. June.

**Presentations by Students**

Lepak, R.F., Yin, R., DeWild, J.F., , Ogorek, J.M., Tate, M.T., Thompson, C.D., Krabbenhoft, D.P., and Hurley, J.P., 2015. The Application of Mercury Stable Isotopes to Lake Erie: Improving Our Understanding of Mercury Sources,

Cycling, and Processes. Twelfth International Conference on Mercury as a Global Pollutant. Jeju, Korea. June. (3) Thompson, C.D., Lepak, R.F., Yin, R., Krabbenhoft, D.P., DeWild J.F., Maglio, M.M., Ogorek, J.M., Tate M.T., Hurley, J.P., Nationwide Trends in Mass-dependent and Mass-independent Mercury Isotope Fractionation in Lacustrine Sediments from USEPA National Lake Assessment, Poster Presentation, International Conference for Mercury as a Global Pollutant, Jeju Korea, June 16th, 2015 (primary presenter).

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**Title**  
International Association for Great Lakes Research Conference

**Location**  
Burlington, Vermont

**Dates**  
May 26, 2015

**Number of supported students attending**  
1

**Presentations by Students**  
Lepak, R.F., Yin, R., DeWild, J.F., , Ogorek, J.M., Tate, M.T., Thompson, C.D., Krabbenhoft, D.P., and Hurley, J.P., Utilizing Ambient Mercury Stable Isotopes in Lake Erie, Oral Presentation, International Association for Great Lakes Research Conference, Burlington, Vermont, May 26, 2015.

**Journal Articles and Other Publications**

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**Title**  
Sedimentary Records of Mercury Stable Isotopes in Lake Michigan.

**Type of Publication**  
Book or Monograph (Peer-reviewed)

**Complete Citation**  
Yin R., R.F. Lepak, D.P. Krabbenhoft and J.P. Hurley. 2016. Sedimentary Records of Mercury Stable Isotopes in Lake Michigan. Elementa: Science of the Anthropocene 4.1: 000086.

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**Title**  
Use of Stable Isotope Signatures to Determine Mercury Sources in the Great Lakes.

**Type of Publication**  
Book or Monograph

**Complete Citation**  
Lepak, R.F., R. Yin, R., D.P Krabbenhoft, J.M. Ogorek, J.F. DeWild, T.M. Holsen, and J.P. Hurley 2015. Use of Stable Isotope Signatures to Determine Mercury Sources in the Great Lakes. Environmental Science and Technology Letters 2:335–341.

**Awards and Achievements**

No awards and achievements reported.

**Research Patent or Copyright**

No research patents or copyrights reported.

# **Information Transfer Program Introduction**

None.

# University of Wisconsin Water Resources Institute - 5 Year Information Transfer Program

## Basic Information

<b>Title:</b>	University of Wisconsin Water Resources Institute - 5 Year Information Transfer Program
<b>Project Number:</b>	2011WI265B
<b>Start Date:</b>	3/1/2015
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	WI-2
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Education, Climatological Processes, Groundwater
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Moira Harrington

## Publications

1. White, Elizabeth; Carolyn Rumery Betz; Aaron Conklin; Moira Harrington; Ann Moser. 2011, Volume 1 Aquatic Sciences Chronicle 8 pages
2. White, Elizabeth; Carolyn Rumery Betz; Aaron Conklin; Moira Harrington; Ann Moser. 2011, Volume 2 Aquatic Sciences Chronicle 8 pages
3. White, Elizabeth; Carolyn Rumery Betz; Aaron Conklin; Moira Harrington; Ann Moser. 2011, Volume 3 Aquatic Sciences Chronicle 10 pages
4. White, Elizabeth; Carolyn Rumery Betz; Aaron Conklin; Moira Harrington; John Karl; Ann Moser. 2011, Volume 4 Aquatic Sciences Chronicle 12 pages
5. Karl, John Streams Neutralize Nitrates in Groundwater 2011 5:51-minute video
6. Harrington, Moira; Aaron Conklin. [wri.wisc.edu](http://wri.wisc.edu) program website
7. Moser, Anne; Sarah Leeman. [aqua.wisc.edu/waterlibrary](http://aqua.wisc.edu/waterlibrary) program website
8. Conklin, Aaron; Carolyn Rumery Betz; Moira Harrington. [facebook.com/UWiscSeaGrant](https://facebook.com/UWiscSeaGrant) Facebook page for University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute
9. Conklin, Aaron; Carolyn Rumery Betz, Moira Harrington. @UWiscSeaGrant Twitter address for both University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute
10. Rumery Betz, Carolyn; et al. 2011, 35th Annual Meeting Program and Abstracts Wisconsin's Role in Great Lakes Restoration, American Water Resources Association, Wisconsin Section. 76 pages
11. Babiarz, Christopher; James P. Hurley; David P. Krabbenhoft; James G. Wiener July, 19, 2011, Wisconsin Leads the World in Mercury Research opinion-page column, 2 pages
12. Rumery Betz, Carolyn; Kevin Masarik. March 7, 2011 Spring is a Good Time to Test Well Water news release, 2 pages
13. Rumery Betz, Carolyn; Kevin Masarik. March 2, 2011 Celebrate Groundwater Awareness Week by Properly Filling and Sealing Unused Wells news release 2 pages
14. Rumery Betz, Carolyn; Kevin Masarik March 1, 2011 Dispelling Groundwater Myths news release 2 pages

## University of Wisconsin Water Resources Institute - 5 Year Information Transfer Program

15. White, Elizabeth; Aaron Conklin; Moira Harrington; Ann Moser; Marie Zhuikov 2012, Volume 2 Aquatic Sciences Chronicle 12 pages
16. White, Elizabeth; Aaron Conklin; Moira Harrington; Ann Moser; Marie Zhuikov 2012, Volume 3 Aquatic Sciences Chronicle 12 pages
17. White, Elizabeth; Aaron Conklin; Moira Harrington; Ann Moser; Marie Zhuikov 2012, Volume 4 Aquatic Sciences Chronicle 12 pages
18. White, Elizabeth; Aaron Conklin; Moira Harrington; John Karl; Ann Moser; Marie Zhuikov 2013, Volume 1 Aquatic Sciences Chronicle 8 pages
19. Karl, John What's a Spring 2012 27-second video
20. Harrington, Moira; Aaron Conklin; Marie Zhuikov wri.wisc.edu program website
21. Moser, Anne; Peter Rudrud aqua.wisc.edu/waterlibrary program website
22. Moser, Anne water.wisc.edu portal website
23. Conklin, Aaron; Marie Zhuikov; Moira Harrington facebook.com/UWiscSeaGrant Facebook page for University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute
24. Conklin, Aaron; Marie Zhuikov; Moira Harrington @UWiscSeaGrant Twitter handle for both University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute
25. Moser, Anne. @WiscWaterLib Twitter handle for Wisconsin's Water Library
26. Moser, Anne. Facebook page for Wisconsin's Water Library facebook.com/WiscWaterLib
27. White, Elizabeth; et al. 2012, 36th Annual Meeting Program and Abstracts Science-Based Policy for Wisconsin's Water Resources, American Water Resources Association, Wisconsin Section. 93 pages
28. Andren, Anders March 7, 2012, Consider the Tide Under Your Feet, opinion-page column, 2 pages
29. Harrington, Moira April 9, 2012 New Director of Sea Grant Institute and Water Resources Institute Chosen news release, 2 pages
30. Zhuikov, Marie January 2, 2013 Study Shows Mercury Deposited Into Lakes Quickly Finds Its Way Into Fish news release, 2 pages
31. Babiarz, Chris; Marie Zhuikov October 2012 Nitrates in Groundwater fact sheet, 4 pages
32. Babiarz, Chris; Marie Zhuikov October 2012 Arsenic in Groundwater fact sheet 4 pages
33. White, Elizabeth; Aaron Conklin; Moira Harrington; Anne Moser; Marie Zhuikov, 2013 Volume 2 Aquatic Science Chronicle, 8 pages
34. White, Elizabeth; Aaron Conklin; Moira Harrington; Anne Moser; Marie Zhuikov, 2013, Volume 3 Aquatic Sciences Chronicle 8 pages
35. White, Elizabeth; Aaron Conklin; Moira Harrington; Anne Moser; Marie Zhuikov, 2013 Volume 4 Aquatic Sciences Chronicle 12 pages
36. White, Elizabeth; Aaron Conklin; Moira Harrington; Anne Moser; Marie Zhuikov, 2014 Volume 1 Aquatic Sciences Chronicle 8 pages
37. Zhuikov, Marie June 13, 2013 Climate Change is Focus of New Water Resources Institute Projects, news release 1 page
38. Harrington, Moira June 26, 2013 Downloadable, Free Resource on Flooding news release 1 page
39. Zhuikov, Marie July 10, 2013 Ancient Oaks Help Scientists Study Climate in Southwestern Wisconsin news release 1 page
40. Zhuikov, Marie January 14, 2014 Researchers Find Strontium in Northeastern Wisconsin Wells news release 2 pages
41. White, Elizabeth; et al. 2013 37th Annual Meeting Program and Abstracts Managing Wisconsin's Urban Water Resources American Water Resources Association, Wisconsin Section, 86 pages
42. Harrington, Moira; Aaron Conklin, Marie Zhuikov wri.wisc.edu program website
43. Moser, Anne; Erin Anthony aqua.wisc.edu/water library program website
44. Moser, Anne water.wisc.edu portal website
45. Conklin, Aaron; Moira Harrington, Marie Zhuikov facebook.com/UWiscSeaGrant Facebook page for the University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute

## University of Wisconsin Water Resources Institute - 5 Year Information Transfer Program

46. Conklin, Aaron; Moira Harrington, Marie Zhuikov @UWiscSeaGrant Twitter handle for the University of Wisconsin Water Resources Institute and the Wisconsin Sea Grant Institute
47. Conklin, Aaron; Moira Harrington, Marie Zhuikov @UWiscSeaGrant Twitter handle for the University of Wisconsin Water Resources Institute and the Wisconsin Sea Grant Institute
48. Moser, Anne @WiscWaterLib Twitter handle for Wisconsin's Water Library
49. Moser, Anne facebook.com/WiscWaterLib, Facebook page for Wisconsin's Water Library
50. Bocast, Chris February 28, 2014 Groundwater, Soil and Dr. Dirt 22:34 minute audio podcast
51. Bocast, Chris February 28, 2014 Aquifers, Websites and Water Tables 11:15 minute audio podcast
52. Bocast, Chris February 28, 2014 Waters Within Waters - Working With Watersheds 15:33 minute audio podcast
53. Karl, John Look Ma! No Hands! Remote Water Quality Monitoring 25:41 minute video
54. Karl, John Automation for the People: pH, Alkalinity and Conductivity 14:09 minute video
55. Karl, John The Phosphorous (Analysis) Blues 44:58 minute video
56. Karl, John Come On In! The Water's Fine! Or Is It? (Part One) 18:40 minute video
57. Karl, John Come On In! The Water's Fine! Or Is It? (Part Two) 40:32 minute video
58. Karl, John Keeping it Clean: Techniques and Laboratory Practices for Mercury Analysis 23:39 minute video
59. Karl, John Toxic and Tricky: Analyzing Methylmercury 19:48 minute video
60. Karl, John Going for the Gold III 21:32 minute video
61. Karl, John Analyzing Water for Organic Chemicals 1:22:37 minute video
62. White, Elizabeth; et al. 2014 38th Annual Meeting Program and Abstracts Mining and Wisconsin and Waters Water Resources Association, Wisconsin Section, 78 pages
63. Harrington, Moira; Aaron Conklin, Marie Zhuikov wri.wisc.edu program website
64. Moser, Anne; Jenna Assmus aqua.wisc.edu/water library program website
65. Moser, Anne water.wisc.edu portal website
66. Conklin, Aaron; Moira Harrington, Marie Zhuikov facebook.com/UWiscSeaGrant Facebook page for the University of Wisconsin Water Resources Institute and University of Wisconsin Sea Grant Institute
67. Moser, Anne @WiscWaterLib Twitter handle for Wisconsin's Water Library
68. Moser, Anne facebook.com/WiscWaterLib, Facebook page for Wisconsin's Water Library
69. Bocast, Chris March 6, 2014 Streams, Snails and Invasive Species 19:01 minute audio podcast
70. Bocast, Chris March 31, 2014 Wisconsin Aquifers: Surficial Groundwater and the Central Sands 20:10 minute audio podcast
71. Bocast, Chris March 31, 2014 Wisconsin Aquifers: Cambrian, Pre-Cambrian and Confined 15:40 minute audio podcast
72. Bocast, Chris May 19, 2014 Phosphorous, Outreach and the Fox-Wolf Watershed 24:18 minute audio podcast
73. Bocast, Chris July 2, 2014 Watersheds Past – Oaks, Rings and Answers 21:32 minute audio podcast
74. Karl, John June 16, 2014 Got Oaks? 1:45 minute video
75. Karl, John July 16, 2014 Drought in Southwest Wisconsin As Told By Oaks (And How You Can Help) 3:10 minute video
76. Harrington, Moira Sept. 28, 2015 Milwaukee Public Library, Bay View Branch, to Host Water Photo Display news release
77. Harrington, Moira Aug. 6, 2015 Water Researcher Secures NSF Grant to Study BPA and a CAFO Byproduct news release
78. Harrington Moira July 17, 2015 Rio Library Director Displays Her Love (and Knowledge) of Water Through New Video news release
79. Harrington Moira Aug. 27, 2015 Five New UW Studies Aim to Protect and Better Manage Wisconsin's Wealth of Water news release
80. Harrington Moira Jan. 17, 2016 New Berlin Public Library to Host Water Photo Display news release

## University of Wisconsin Water Resources Institute - 5 Year Information Transfer Program

81. Harrington Moira Aug. 27, 2015 Little Plover River Area the Site of New Research About Making Controversial Water-Use Decisions news release
82. Harrington, Moira March 4, 2015 Annual Well Checks and Groundwater Protection Highlighted During National Groundwater Awareness Week news release
83. Harrington, Moira Aug. 27, 2015 UW-Madison Researchers to Lead Studies That Aim to Protect and Better Manage Wisconsin's Water Wealth news release
84. Harrington, Moira Aug. 28, 2015 UW-Oshkosh Researcher to Look for Clues About How Water Can Be Naturally Cleansed of Agricultural Inputs news release
85. Harrington, Moira Oct. 22, 2015 Middleton Public Library to Host Wisconsin Water Photo Display news release
86. Harrington, Moira Oct. 27, 2015 Rising Water Temperatures Change Timing of Fish Migrations news release
87. Harrington, Moira Dec. 28, 2015 Monona Public Library to Host Wisconsin Water Photo Display news release
88. Harrington, Moira; Aaron Conklin, Marie Zhuikov [wri.wisc.edu](http://wri.wisc.edu) program website
89. Moser, Anne; Sigrid Peterson [aqua.wisc.edu/waterlibrary](http://aqua.wisc.edu/waterlibrary) program website
90. Moser, Anne [water.wisc.edu](http://water.wisc.edu) UW-Madison portal website
91. Conklin, Aaron; Moira Harrington, Marie Zhuikov [facebook.com/UWiscseagrant](https://facebook.com/UWiscseagrant) Facebook account
92. Conklin, Aaron; Moira Harrington @Uwiscseagrant Twitter handle for WRI Twitter account
93. Moser, Anne; Sigrid Peterson @wiscwaterlib Wisconsin Water Library Twitter handle for Twitter account
94. Moser, Anne; Sigrid Peterson [facebook.com/wiscwaterlib](https://facebook.com/wiscwaterlib) Facebook account for Wisconsin Water Library
95. White, Elizabeth; et al Wisconsin Water Resources and Agriculture Wisconsin Chapter of the American Water Resources Association annual conference program 72 pages
96. White, Elizabeth; Aaron Conklin, Moira Harrington, Anne Moser, Marie Zhuikov, 2015 Volume 2 Aquatic Sciences Chronicle 12 pages
97. White, Elizabeth; Aaron Conklin, Moira Harrington, Anne Moser, Marie Zhuikov, 2015 Volume 3 Aquatic Sciences Chronicle 12 pages
98. White, Elizabeth; Aaron Conklin, Moira Harrington, Anne Moser, Marie Zhuikov, 2015 Volume 4 Aquatic Sciences Chronicle 12 pages
99. White, Elizabeth; Aaron Conklin, Moira Harrington, Anne Moser, Marie Zhuikov, 2016 Volume 1 Aquatic Sciences Chronicle 12 pages

The University of Wisconsin Water Resources Institute (WRI) Information Transfer Program ensures delivery of education and outreach related to long-term water planning, policy development and resource management to water researchers, professionals and resource managers. Another target audience is broad—members of the general public—so as to deepen knowledge of Wisconsin's water assets and engender greater stewardship. It is an ongoing project.

In this reporting period, the information transfer program relied on publications, social media, video and audio podcasts, a statewide water resources conference, websites, Wisconsin's Water Library and its full suite of services for water-interested patrons, a photography display, media relations and public presentations to efficiently and effectively attain its goals.

Much of WRI's information is shared via an online publication store, <http://aqua.wisc.edu/publications>. A publication about rain gardens was the most popular WRI download in the publications store. There were about 1,920 downloads in this reporting period. Additional items were distributed through the mail. These included items such as bookmarks, aquatic invasive species watch cards, posters and brochures.

Another publication is the Aquatic Sciences Chronicle, which is produced and distributed quarterly. It highlights water research and the people who conduct water research and outreach. The Chronicle's dedicated consumers consist of roughly 5,700 online and print subscribers, which includes local and state water management agencies, and water-related non-governmental organizations. Readers are found in Wisconsin and across the country. The newsletters are also posted online. At [aqua.wisc.edu/chronicle](http://aqua.wisc.edu/chronicle), all issues of the publication are archived and searchable. There were nearly 40,000 online visitors to the newsletter in the last year.

Social media offers the means to communicate in real time and without traditional editorial filters. WRI is very active on Facebook and Twitter. Through the Twitter account, for example, one analytical tool shows that WRI has the potential to deliver about 700,000 impressions a week. WRI also uses the social media tools Flickr, YouTube, Pinterest and Sound Cloud.

WRI's video catalog includes "What's a Spring," "Streams Neutralize Nitrates in Groundwater," "A New Measure of Groundwater Flow," "Got Oaks" and "Drought in Southwest Wisconsin as Told by Oaks." "Testing Well Water for Microorganisms" is the most popular video in the catalog. To date, it has nearly 9,500 views, which is a large number for a video on a scientific topic. All of the videos are shared through the program's website and its YouTube channel, <http://www.youtube.com/user/UWASC/>.

WRI has also created 11 videos highlighting the protocols of in-laboratory water testing. The video segments were shot at two USGS labs, a regional and a national one; the Wisconsin State Laboratory of Hygiene to focus on algal toxins and metals analysis; and the Racine Public Health Laboratory to explore Great Lakes issues.

WRI's director has used the video in classroom instruction and will do so again in the future. He has received positive feedback from students. That's important since increasingly restricted budgets mean that some laboratory equipment is not being purchased and used as frequently as in the past. Students may not typically be exposed to the equipment and the ways in which it

can be used. In the absence of the opportunity for hands-on interaction, the video can at least provide a chance to see the equipment.

At <http://www.seagrant.wisc.edu/home/Default.aspx?tabid=601&AudioGroupID=33>, visitors can download a WRI-sponsored seven-part audio podcast series. “Water, Wisconsin and the Mercury Cycle” details mankind’s historic uses of mercury, Wisconsin’s water resources and mercury in Wisconsin waters. A major part of the series also focuses on WRI-funded research on mercury.

WRI also produced an eight-episode “Aquifers and Watersheds” audio podcast series, which demystifies for general audiences these geological formations and the geoscience involved in studying them. Episodes are at [bit.ly/1e5a1jQ](http://bit.ly/1e5a1jQ).

Finally, in this reporting period, a new audio podcast series was initiated and it will be completed in the 2016-17 reporting period. It is called “Undercurrents: The Hidden Knowledge of Groundwater.”

WRI posts these audio podcasts on the Web. It also shares them through an iTunes university site. There, WRI has been able to garner its own artist’s page for its podcasts. Pages such as these are reserved only for those contributors who reach a certain threshold of content. The special pages allow for a richer display of water-related content. Moreover, the artist’s page provides a so-called “sticky” experience where users are attracted to the site and then stick around for additional, related information.

The WRI website <http://www.wri.wisc.edu> orients visitors to the Wisconsin program. One of the site’s main audiences is researchers. To that end, the site provides a clear navigational path to the WRI project listing, project reports, a groundwater research database, funding opportunities and conference information sections. The areas are updated on a regular basis to ensure currency of information transfer. The WRI site had an estimated 50,550 visitors in this reporting period.

### **AWRA 2015 Annual Conference**

The Wisconsin Section of the American Water Resources Association conducts an annual meeting. WRI assisted with meeting planning and provides printed material. That means WRI took the lead on writing, editing, providing graphic design, printing and mailing of a conference registration brochure, and the writing, editing, graphic design and printing of the conference program. WRI joined other conference sponsors—the University of Wisconsin-Stevens Point Center for Watershed Science and Education, Wisconsin Department of Natural Resources, Wisconsin Geological and Natural History Survey and the U.S. Geological Survey’s Wisconsin Water Science Center—to stage the event that attracted about 200 people.

### **Post-Secondary Students Engaged in Water Education**

During this reporting period, WRI staff were also integral to the content-population of <http://www.water.wisc.edu>. The site is a portal to the breadth and depth of water-related work on the University of Wisconsin System’s flagship campus, the University of Wisconsin-Madison, and serves as the first stop for anyone interested in water research. Additionally, graduate students can search for departments offering courses and degrees that fit their interests, and

staff and faculty can search for colleagues working on topics complementary to their own to facilitate greater interdisciplinary collaboration and exploration. The site had an estimated 44,850 visitors in this reporting period.

Building off of this website and the collaborative nature of its contributors, WRI staff provided leadership in launching Water@UWMadison – A Wisconsin Idea Symposium, an event designed to bring water researchers and faculty from around the UW-Madison campus together to build awareness and collaboration.

Fifty water and water-related investigators from all divisions on campus presented to an audience of fellow academicians, elected officials and interested members of the public, including those representing water-centric non-governmental organizations. There were approximately 150 people in the audience. A white paper resulted from that symposium and in it was a recommendation to the chancellor that a water coordinator position be created to capitalize on the value of water scholarship. That position was approved late in this reporting period and represents a positive step in providing a liaison for those interested in water scholarship, whether it be researchers, resource managers, policymakers or students.

### **Wisconsin's Water Library**

Wisconsin's Water Library is a unique resource for researchers, resource managers and all Wisconsin citizens. It contains more 30,000 volumes of water-related information about the Great Lakes and other waters of Wisconsin. The library includes a curricula collection, dozens of educational videos, children's collection, five journals and 30 newsletters. Each year, about 1,400 publications circulate among interested patrons.

Wisconsin's Water Library continues to catalog all groundwater research reports from WRI projects into WorldCat and MadCat, two library-indexing tools. This ensures WRI's cutting-edge water exploration is broadly available locally, regionally, nationally and even internationally.

In addition to archival benefits, the library provides outreach by answering many in-depth reference questions on a wide range of water-related topics. It provides a water research guide (<http://researchguides.library.wisc.edu/waterresearchguide>). It is active on social media and goes out into the community to offer presentations (more on that below). It prepares recommended reading lists on topics such as climate change, groundwater, water conservation and water supply.

In partnership with the Wisconsin Department of Natural Resources and the Wisconsin Wastewater Operator's Association (WWOA), the library has continued its long-term assistance to current and future drinking water and wastewater operators in Wisconsin. The library has cataloged the essential technical manuals into the library's collection and provides loans to WWOA members around the state in support of their required state license examinations as well as in support of the educational needs of their daily work. In this reporting period, 32 professionals used this invaluable professional development service.

The library maintains several information transfer tools to reach library patrons and the most frequently accessed is the library's website, <http://www.aqua.wisc.edu/waterlibrary>. There were 186,750 visitors in this reporting period.

In addition to its website, Wisconsin's Water Library uses other technology tools to reach library patrons. Using email, the library sends out a bimonthly "Recent Acquisitions List" to roughly 500 contacts. The message also includes recent updates to the library website and contact information for users to ask any water-related question. The library also supports an email account at [askwater@aqu.wisc.edu](mailto:askwater@aqu.wisc.edu), which is monitored daily.

Finally, the library maintains an extensive curriculum collection of guides with innovative approaches and other educational materials for teaching water-related science in K-12 classrooms. The curricula are available for checkout by all teachers and residents in Wisconsin. The librarian also has extensive experience in working with Pre-K children. She has put that experience to use in developing already field-tested science, technology, engineering, art and math (STE(A)M) curriculum kits. The kits will eventually number 27 on topics such as the water cycle, art and water, and pond science. In this reporting period, kits related to ponds and to buoyancy were completed. The kits contain several books, tips on a guided water-science experiment and other themed activities.

## **Outreach Events**

To build water literacy, Wisconsin's Water Library and other information transfer staff reached approximately 350 Wisconsin residents through nine events conducted at public libraries, Head Start and other early-childhood programs, and as part of other informal learning settings. Staff also delivered presentations to Head Start and environmental education instructors. This sparked inquiries from 14 teachers across Wisconsin who were interested in STE(A)M literacy. It demonstrates multiplier effect, that is, if each teacher then reached a minimum of 10 students or lifelong learners nearly an additional 150 people benefitted from water education.

## **Notable Accomplishments**

1. WRI created a traveling photography exhibit in the prior reporting period. Photography is a powerful way to communicate. This exhibit is a stand-alone tool depicting stunning scenes of Wisconsin's water assets and highlighting work that WRI and its sister organization Wisconsin Sea Grant.

The exhibit is on its second year of bookings and continues to remain popular, with requests to host it coming in at least monthly. So far, it has traveled to nature centers, public libraries and conferences and will do so until the conclusion of 2016. At each stop, a news release is distributed to local media and local residents are invited to view the exhibit. There are accompanying handouts to encourage further interaction through Water Resources Institute publications, websites, podcasts or video. Staff are offered as speakers in conjunction with the exhibit's run at a specific venue. In this reporting period, staff delivered five presentations and in one location, the hosts used the exhibit as a springboard to set up their own water-themed events. The display itself has been positively evaluated since a formal set of questions are always circulated to the hosts to encourage feedback. One Milwaukee host venue wrote, "Bay View Library attracts an average of 500 visitors a day. The display was in a place where most visitors could see it and choose to take a closer look at it. I noticed at least a couple of visitors a day who

came to the library specifically because of the display and took the information handouts to follow up by checking websites listed.”

2. Information transfer program professionals engage in media relations to ensure that water-related messages are shared with varied audiences in varied ways. That builds brand awareness for WRI as a trusted purveyor of knowledge. In this reporting period, one of the information transfer staff members recognized the news value of an unfortunate event—the water crisis in Flint, Mich.—and turned it into a teaching tool. She put forward the WRI director as a source for media outlets and was able to secure two newspaper interviews, a live television interview and a radio interview—all in large Wisconsin media markets.

# Recent Advances in Monitoring and Analysis of Trace Metals: A Workshop to Address Applications in the Upper Great Lakes

## Basic Information

<b>Title:</b>	Recent Advances in Monitoring and Analysis of Trace Metals: A Workshop to Address Applications in the Upper Great Lakes
<b>Project Number:</b>	2014WI325B
<b>Start Date:</b>	3/1/2015
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	WI 2nd
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Water Quality, Geochemical Processes, Surface Water
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Stephen J. Ventura

## Publication

1. Cardiff, S.G., and Lepak, R.F. 2015. Summary of the Workshop on Trace Metals Monitoring in the Lake Superior Basin. <http://www.lic.wisc.edu/glifwc/workshops/tracemetals.html>.

# Report on "Recent Advances in Monitoring and Analysis of Trace Metals: a Workshop to Address Applications in the Upper Great Lakes"

**Reporting Period:** 3/1/2015 - 2/29/2016

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## **Project**

WR14R001 - Recent Advances in Monitoring and Analysis of Trace Metals: A Workshop to Address Applications in the Upper Midwest

## **Principle Findings and Significance**

The objective of this project was to facilitate the sharing of information on current work, methods, and results for the study and monitoring of trace metals and related constituents in the Upper Great Lakes and their watersheds. We expected the project to improve research planning and methods for new projects and increase information sharing and coordination between researchers and managers.

In order to accomplish this, we organized a workshop on Trace Metals Monitoring in the Lake Superior Basin the 12-13 November 2015 in Odanah on the Bad River Reservation, northern Wisconsin. The workshop featured 17 presentations, additional discussion on certain topics, and exchange of research articles. Fifty people participated in-person and an additional 20 people participated in the webinar associated with the workshop. Participants included staff from Native, state, and Federal agencies as well as academic researchers and students.

The presentations and discussions at the workshop addressed a number of considerations and advanced techniques of importance in monitoring for metal(loid)s and related constituents in water and sediment. Important concepts covered included sampling considerations, the advantages of magnetic sector inductively couple plasma mass spectrometry (ICP-MS) instruments, and the availability of relatively new geochemical fingerprinting techniques such as the use of trace metal stable isotopes. The presentations also provided an overview of some of the broad range of metals research projects in the region.

Recommendations in the workshop summary document, in addition to the other information shared during the workshop, will help participants in understanding the results of trace metals studies and help them plan their own research and monitoring activities with advanced techniques where relevant. The case studies presented during the workshop also helped update researchers and agency staff active in the region on existing research and recent trace metals results. Finally, the workshop allowed for participants to develop working relationships that should help improve future flow of information on study results and new techniques for the study of trace metals in water and sediment in the region.

## **Number of Personnel Involved**

3 Participating faculty/staff

0 Supported post-docs

Students Supported

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Name

Scott Cardiff

Affiliation

University of Wisconsin-Madison

Degree

PhD/DSci

Major/Specialization

Environment and Resources

Graduation

12/2016

Thesis Title

Cumulative Land Cover and Water Quality Impacts of Large-scale Mining in Lake Superior Ojibwe Treaty-ceded Territories

Conference Participation

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Title

“Monitoring Trace Metals in the Lake Superior Basin – An Assessment of Techniques and Case Studies”

Location

Odanah, WI

Dates

12-13 November 2015

Number of supported students attending

1

Presentations by Staff

Shafer, Martin. Analytical Tools and Approaches for Assessment of Levels and Speciation of Trace Elements in Water- and Air-sheds of the Great Lakes.

Presentations by Students

Lepak, Ryan, and Hurley, Jim. Use of Stable Isotope Signatures to Determine Mercury Sources in the Great Lakes.

Journal Articles and Other Publications

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Title

Summary of the Workshop on Trace Metals Monitoring in the Lake Superior Basin

## Type of Publication

Media Placement, Press Release or Newspaper Story

## Complete Citation

Cardiff, S.G., and Lepak, R.F. Summary of the Workshop on Trace Metals Monitoring in the Lake Superior Basin.  
<http://www.lic.wisc.edu/glifwc/workshops/tracemetals.html>

## Awards and Achievements

No awards and achievements reported.

## Research Patent or Copyright

No research patents or copyrights reported.

## Completion Summary

The workshop succeeded in assembling a relevant suite of researchers and agency staff from around the Lake Superior region to discuss advanced techniques for analysis of trace metals and related case studies. A summary of the workshop highlighted several recommendations for methods in future work on trace metals in the region. Those recommendations included the following:

- Ensure that field sampling captures temporal and spatial variability;
- Ensure that sampling and analysis include enough samples, sample volume, and constituents for addressing the research question (e.g., comprehensive dissolved analyses for geochemical modeling, dissolved organic carbon and other constituents for the biotic ligand model (BLM), etc.);
- Ensure that the laboratory method for determining concentrations is sensitive and comprehensive enough for the research question (e.g., ICP- Optical/Atomic Emission Spectrometry (AES/OES) vs. quadrupole ICP-MS vs. magnetic sector ICP-MS);
- Consider use of isotope enrichment for investigating processes an analyte may undergo and for more accurate quantification of complex matrices with potential interferences (matrix match field-spiked analytes if possible).
- For fingerprinting to determine trace metal sources,
  - carefully assess which type of tracer would be most useful for the research question (e.g. ratios of concentrations and multivariate analyses vs. stable isotope analyses),
  - determine likely end-member sources and if their characterization is feasible;
- For fingerprinting with trace metal stable isotopes, review information on the isotope fractionation behavior of potential study metals (include consideration of Cd, Cu, Pb, Zn, and Hg) to ensure that
  - Pre-concentration is feasible if the selected metal occurs at very low concentrations,
  - The isotope pattern is likely to differ between the sources to be distinguished, and
  - The isotope pattern is not likely to vary or is likely to vary predictably between the source and the assessment location(s).
- Ensure adequate quality control and assurance throughout

Those recommendations, in addition to the other information shared during the workshop, will help participants in understanding the results of trace metals studies and help them plan their own research and monitoring activities. The case studies presented during the workshop also helped update researchers and agency staff active in the region on existing research and recent trace metals results. Finally, the workshop allowed for participants to develop working relationships that should help improve future flow of information on study results and new

techniques for the study of trace metals in water and sediment in the region.

## **Project Completion Report**

### **Recent Advances in Monitoring and Analysis of Trace Metals: a Workshop to Address Applications in the Upper Great Lakes**

**April 2016**

**Steve Ventura and Scott Cardiff**

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## **PROJECT SUMMARY**

**Title:** Recent Advances in Monitoring and Analysis of Trace Metals: a Workshop to Address Applications in the Upper Great Lakes

**Project I.D.:** WR14R001 (UW Project A075400 144 PRJ81NE)

### **Investigators:**

Principal Investigator -- Stephen J. Ventura, Professor, Department of Soil Science / Nelson Institute for Environmental Studies / Land Information and Computer Graphics Facility

Associate Investigator -- John Coleman, Honorary Associate, University of Wisconsin-Madison and Great Lakes Indian Fish and Wildlife Commission, Odanah, WI

Research Assistant -- Scott Cardiff, Research Assistant, Nelson Institute for Environmental Studies / Land Information and Computer Graphics Facility

### **Period of Contract:**

01 March 2014 – 29 February 2016

### **Background/Need:**

Emergence of clean techniques for trace metals sampling, processing and analysis, together with advances in analytical instrumentation detection limits from the 1990's to the present, have greatly advanced our understanding of trace metal cycling in the environment. Although trace metals are natural components of the earth's crust, anthropogenic influences have greatly altered cycling processes in air, water, and soil. This has resulted in concentrations of certain trace metals and associated constituents in water and sediment that are of concern for humans and ecosystems. To study such trace metals contamination, several recent research investigations have used new, advanced techniques in the Upper Great Lakes region. Given the wide range of activities in the region affecting trace metals, we considered it important to take stock of these methods, discuss successes, and suggest applications for future monitoring and research of significant trace metals processes in the Upper Great Lakes region.

### **Objectives:**

The objective of this project was to facilitate the sharing of information on current work, including sampling and analysis methods, fate and transport models, and results for the study and monitoring of trace metals and related constituents in the Upper Great Lakes and their watersheds. We expected the project to improve research planning and methods for new projects and increase information sharing and coordination between researchers and managers.

### **Methods:**

In order to help share information on monitoring for trace metals in the region, we organized a workshop on Trace Metals Monitoring in the Lake Superior Basin the 12-13 November 2015 in Odanah on the Bad River Reservation, northern Wisconsin. We sought to facilitate information

exchange on advanced trace metals monitoring methods and results between academics and agencies, including Native Nations agencies in the region.

### **Results and Discussion:**

The workshop featured 17 presentations, additional discussion on certain topics, and exchange of research articles. Fifty people participated in-person and an additional 20 people participated in the webinar associated with the workshop. Participants included staff from Native, state, and Federal agencies as well as academic researchers and students.

The presentations and discussions at the workshop addressed a number of considerations and advanced techniques of importance in monitoring for metal(loid)s and related constituents in water and sediment. The workshop also provided an overview of some of the broad range of metals research projects in the region.

The presentations and discussions highlighted several important concepts, including for sampling considerations, the advantages of magnetic sector ICP-MS instruments, and the availability of relatively new geochemical fingerprinting techniques such as the use of trace metal stable isotopes.

### **Conclusions/Implications/ Recommendations:**

The workshop succeeded in assembling a relevant suite of researchers and agency staff from around the focus region to discuss advanced techniques for analysis of trace metals and helpful case studies. Participants exchanged information on methods and results in presentations, discussions, and through the exchange of articles. A summary of the workshop highlighted several recommendations for methods in future work on trace metals in the region.

### **Related Publications:**

Cardiff, S.G. & Lepak, R. 2016. Summary of the Workshop on Trace Metals Monitoring in the Lake Superior Basin. <http://www.lic.wisc.edu/glifwc/workshops/tracemetals.html>

### **Key Words:**

Trace metals, ICP-MS, workshop, conductivity, water sampling, stable isotopes, geochemical fingerprinting, mercury, lead, Lake Superior

### **Funding:**

University of Wisconsin Water Resources Institute (WRI) WR14R001

## INTRODUCTION –

Trace metals in water and sediment of the Upper Great Lakes and their watersheds have been of subject of study for many years (e.g., Sorensen *et al.* 1990, Hurley *et al.* 1995, Powell *et al.* 2000, Kerfoot *et al.* 2004, Parsons *et al.* 2007, McDonald *et al.* 2010, Weaver *et al.* 2010, Babiarz *et al.* 2012, Berndt & Bavin 2012). In spite of this work, many questions on metal distribution, sources, transport, and fate remain unanswered. This includes questions on the sources and cycling of mercury, and the distribution of mining-associated metals (e.g., copper, vanadium), and associated contaminants (e.g., selenium and sulfate).

Advances in methods for the study of trace metals in the last two decades have, however, created opportunities to answer many of those outstanding questions. Those advances include the development of trace metals clean sampling techniques (USEPA 1996, USGS variously dated), and also improvements in resolution of laboratory analyses (Krachler 2007, Popp *et al.* 2010, Páscoa *et al.* 2012). The development of the high resolution (sector-field /magnetic sector) inductively coupled mass spectrometry (ICP-MS) in particular has allowed exploration of more trace metals stable isotopes for purposes of understanding metals cycling and sources (Moldovan *et al.* 2004, Krachler 2007).

The availability of those advanced techniques is also important because trace metals contamination is an ongoing concern in the Upper Great Lakes region. Industrial facilities continue to discharge metals and related constituents and new facilities likely to affect trace metals are also currently under construction or proposed in the region. On Lake Superior, for instance, these include copper-nickel mine projects in Minnesota and Michigan, and iron mine expansion in Minnesota (GLIFWC 2012, MN DNR 2014). The current and potential future sources of trace metals increase the need for rigorous research and monitoring of trace metals and related water quality constituents.

Researchers from a broad range of academic and agency research teams are currently studying various aspects of trace metals in the Upper Great Lakes region. Agencies working on projects studying trace metals and related constituents in Lake Superior and its watershed include the Great Lakes Indian Fish and Wildlife Commission (GLIFWC), resource management departments of individual Native Nations, the US Geological Survey (USGS), US Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA) and various state resource management agencies. Furthermore, several university researchers in the Upper Midwest are conducting studies of trace metals in the Great Lakes and their watersheds. Just in the last few years, researchers have significantly advanced understanding of trace metals topics such as distribution (e.g., Rolffhus *et al.* 2015a, Kerfoot *et al.* 2016), sources (Lepak *et al.* 2015a, Sherman *et al.* 2015) and cycling (Chadwick *et al.* 2013, Lepak *et al.* 2015b, Rolffhus *et al.* 2015b) of mercury and other metals.

Unfortunately, information on current activities, conclusions, preliminary results, and appropriate techniques does not always circulate efficiently between the many different research

and management teams. To help improve dissemination and coordination of that research, we sought to organize a workshop bringing together academic and agency researchers from across the three states in the Lake Superior watershed.

## **PROCEDURES AND METHODS –**

In order to help share information on monitoring for trace metals in the region, we organized a workshop on Trace Metals Monitoring in the Lake Superior Basin the 12-13 November 2015 in Odanah on the Bad River Reservation, northern Wisconsin.

To organize the workshop, we consulted with agency staff and others on specific trace metals monitoring topics of interest. We then reviewed the literature to determine a list of experts on those topics and sought to invite those experts as presenters. Those trace metals topics included sampling, trace metals fingerprinting, and stable isotopes. We also used the snowball approach to identify additional presenters and participants.

In determining the location and timing of the workshop, we sought to ensure that most potential participants could attend. To accomplish this, we checked with individuals on their specific schedules, selected a time of year when much field work had ended and before significant snowfall might prevent some from reaching the workshop, and selected a location that was relatively central for participants coming from both Minnesota and Michigan.

We also sought to minimize barriers to participation by covering presenter and participant costs at the workshop. We also covered travel by some presenters coming from further away.

## **RESULTS AND DISCUSSION**

The workshop featured 17 presentations, additional discussion on certain topics, and exchange of research articles. Fifty people participated in-person and an additional 20 people participated in the webinar associated with the workshop. Participants included staff from Native, state, and Federal agencies as well as academic researchers and students (Table 1).

*Table 1. Summary of the affiliation of participants in the Trace Metals Workshop.*

<b>Affiliation category</b>	<b>Specific affiliation</b>	<b>Number of people in-person</b>	<b>Number of additional people in webinar</b>
Native Nations	1854 Treaty Authority	1	
	Bad River Band of Lake Superior Ojibwe Natural Resources Department	6	
	Bay Mills Indian Community	1	
	Fond du Lac Band of Lake Superior Chippewa	1	
	Grand Portage Band of Ojibwe	1	
	Great Lakes Indian Fish and Wildlife Commission	5	
	Keweenaw Band Indian Community Natural Resources Department	4	
	Lac du Flambeau Band of Lake Superior Chippewa	2	1
	Red Cliff Band of Lake Superior Chippewa	1	1
	Sokoagon Chippewa Community (Mole Lake Band of Lake Superior Chippewa Indians)	1	
U.S. Federal	National Park Service	2	4
	U.S. Geological Survey	4	3
	U.S. Forest Service	2	4
	U.S. Environmental Protection Agency		5
State	Minnesota Department of Natural Resources	1	
	Minnesota Pollution Control Agency	1	
	Wisconsin Department of Natural Resources	3	
Academic	Gustavus Adolphus College	1	
	Michigan Technological University	2	
	Northland College	3	
	University of Minnesota Duluth	1	
	University of Minnesota Twin Cities		1
	University of Wisconsin - La Crosse	1	
	University of Wisconsin – Madison (and WI State Lab of Hygiene)	4	1
	Western Carolina University	1	

Presenters included experts in the fields of trace metals monitoring, geochemistry, laboratory analysis, and geochemical fingerprinting (Table 2). Presentations consisted of six presentations on methods and 11 presentations focusing on case studies in the Great Lakes region (Table 2).

*Table 2. Workshop presenters and presentations.*

<b>Presentation Category</b>	<b>Author(s) and affiliation(s)</b>	<b>Title</b>
Methods	D. Kirk Nordstrom, U.S. Geological Survey	Advances and Applications in Electrical Conductivity Monitoring for Natural Waters
	Martin Shafer, WI State Lab of Hygiene	Analytical Tools and Approaches for Assessment of Levels and Speciation of Trace Elements in Water- and Air-sheds of the Great Lakes
	Richard Wanty, U.S. Geological Survey	Trace Metal Stable Isotopes in Mineral-Environment Investigations
	Jerry Miller, Western Carolina University	Application of Lead Isotopes to Environmental Forensics
	Kathy Smith, U.S. Geological Survey	Challenges in Aquatic Metal Sampling and Toxicity Prediction in Mineralized Areas
	Sara Moses, Great Lakes Indian Fish and Wildlife Commission	Development of GLIFWC's Mercury-based Tribal Fish Consumption Advice
Case studies in WI	Naomi Tillison, Bad River Natural Resources Department	Background Inorganic Investigation in the Bad River Watershed
	Faith Fitzpatrick, Molly Breitmum, Paul C. Reneau, and Eric Dantoin, U.S. Geological Survey	Sampling for Trace Elements in Water and Sediment along a Longitudinal Continuum from the Bad River's Headwaters to its Mouth in Lake Superior
Case studies in MN	Perry Jones, Laurel Woodruff, Sarah Elliott, Robert Seal, III, and Nadine Piatak, U.S. Geological Survey	Assessing the Influence of Copper- and Nickel-bearing Bedrock on Baseline Water Quality in Three Northeastern Minnesota Watersheds
	Michael Berndt, MN DNR	The Sulfate / DOC / Methylmercury Story in a NE Minnesota Watershed Containing Open Pit Mines
	Nathan Johnson, University of Minnesota Duluth	A Snapshot of Mercury Geochemistry in Sediment, Porewater, and Surface Water in the St. Louis River Estuary

	Jeff Jeremiason*, Nathan Johnson, & Dan Fraser; *Gustavus Adolphus College	Mercury in Dragonflies in the St. Louis River Estuary
Case studies in MI	W. Charles Kerfoot*, Noel R. Urban, Cory P. McDonald, Ron Rossmann, and Huanxin Zhang; *Michigan Technological Univ.	Early Industrial Revolution Mercury Releases During Copper Mining Near Lake Superior
	Noel Urban*, W.C. Kerfoot, J.A. Perlinger, A. Mandelia, J. Rickli, & W. Alakayak; *Michigan Technological Univ.	Effects of Mining on Trace Metal Concentrations in Surface Environments of Michigan's Upper Peninsula
Regional case studies	Kristofer Rolhus, University of Wisconsin-LaCrosse	Mercury in Aquatic Food Webs of Six National Parks of the Western Great Lakes Region
	Jacob Ogorek*, David Krabbenhoft, John DeWild, Michael Tate, Charlie Thompson, Morgan Maglio, Ryan Lepak, and Glenn Warren; *U.S. Geological Survey	A Synopsis of Mercury in Lake Superior
	Ryan Lepak and Jim Hurley, University of Wisconsin-Madison	Use of Stable Isotope Signatures to Determine Mercury Sources in the Great Lakes

The presentations and discussions at the workshop addressed a number of considerations and advanced techniques of importance in monitoring for metal(loid)s and related constituents in water and sediment. The workshop highlighted several important concepts, including related to sampling considerations, the advantages of magnetic sector ICP-MS instruments, and the availability of relatively new geochemical fingerprinting techniques such as the use of trace metal stable isotopes. The presentations also provided an overview of some of the broad range of metals research projects in the region.

## CONCLUSIONS AND RECOMMENDATIONS –

The workshop succeeded in assembling a relevant suite of researchers and agency staff from around the Lake Superior region to discuss advanced techniques for analysis of trace metals and related case studies. A summary of the workshop highlighted several recommendations for methods in future work on trace metals in the region. Those recommendations included the following:

- Ensure that field sampling captures temporal and spatial variability;
- Ensure that sampling and analysis include enough samples, sample volume, and constituents for addressing the research question (e.g., comprehensive dissolved analyses for geochemical modeling, DOC and other constituents for the BLM, etc.);
- Ensure that the laboratory method for determining concentrations is sensitive and comprehensive enough for the research question (e.g., ICP-AES/OES vs. quadrupole ICP-MS vs. magnetic sector ICP-MS);
- For fingerprinting to determine trace metal sources,
  - carefully assess which type of tracer would be most useful for the research question (e.g., ratios of concentrations and multivariate analyses vs. stable isotope analyses),
  - determine likely end-member sources and if their characterization is feasible;
- For fingerprinting with trace metal stable isotopes, review information on the isotope fractionation behavior of potential study metals (include consideration of Cd, Cu, Pb, Zn, and Hg) to ensure that
  - Pre-concentration is feasible if the selected metal occurs at very low concentrations,
  - The isotope pattern is likely to differ between the sources to be distinguished, and
  - The isotope pattern is not likely to vary or is likely to vary predictably between the source and the assessment location(s).
- Ensure adequate quality control and assurance throughout

These recommendations, in addition to the other information shared during the workshop, will help participants in understanding the results of trace metals studies and help them plan their own research and monitoring activities. The case studies presented during the workshop also helped update researchers and agency staff active in the region on existing research and recent trace metals results. Finally, the workshop allowed for participants to develop working relationships that should help improve future flow of information on study results and new techniques for the study of trace metals in water and sediment in the region.

## REFERENCES –

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## **APPENDIX A: Publications, Presentations, Students, Impact**

### **1) Publication:**

Cardiff, S.G. & Lepak, R. 2016. Summary of the Workshop on Trace Metals Monitoring in the Lake Superior Basin. <http://www.lic.wisc.edu/glifwc/workshops/tracemetals.html>

### **2) Presentations:**

Berndt, M. 2015. The Sulfate / DOC / Methylmercury Story in a NE Minnesota Watershed Containing Open Pit Mines. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Fitzpatrick, F., Breitmun, M., Reneau, P.C., and Dantoin, E. 2015. Sampling for Trace Elements in Water and Sediment along a Longitudinal Continuum from the Bad River's Headwaters to its Mouth in Lake Superior. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Jeremiason, J., Johnson, N., & Fraser, D. 2015. Mercury in Dragonflies in the St. Louis River Estuary. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Johnson, N. 2015. A Snapshot of Mercury Geochemistry in Sediment, Porewater, and Surface Water in the St. Louis River Estuary. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Jones, P., Woodruff, L., Elliott, S., Seal, III, R., and Piatak, N. 2015. Assessing the Influence of Copper- and Nickel-bearing Bedrock on Baseline Water Quality in Three Northeastern Minnesota Watersheds. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Kerfoot, W.C., Urban, N.R., McDonald, C.P., Rossmann, R., and Zhang, H. 2015. Early Industrial Revolution Mercury Releases during Copper Mining near Lake Superior. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Lepak, R., and Hurley, J. 2015. Use of Stable Isotope Signatures to Determine Mercury Sources in the Great Lakes. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Miller, J. 2015. Application of Lead Isotopes to Environmental Forensics. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Moses, S. 2015. Development of GLIFWC's Mercury-based Tribal Fish Consumption Advice. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Nordstrom, D.K. 2015. Advances and Applications in Electrical Conductivity Monitoring for Natural Waters. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Ogorek, J., Krabbenhoft, D., DeWild, J., Tate, M., Thompson, C., Maglio, M., Lepak, R., and Warren, G. 2015. A Synopsis of Mercury in Lake Superior. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Rolfhus, K. 2015. Mercury in Aquatic Food Webs of Six National Parks of the Western Great Lakes Region. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Shafer, M. 2015. Analytical Tools and Approaches for Assessment of Levels and Speciation of Trace Elements in Water- and Air-sheds of the Great Lakes. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Smith, K. 2015. Challenges in Aquatic Metal Sampling and Toxicity Prediction in Mineralized Areas. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Tillison, N. 2015. Background Inorganic Investigation in the Bad River Watershed. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Urban, N., Kerfoot, W.C., Perlinger, J.A., Mandelia, A., Rickli, J., & Alakayak, W. 2015. Effects of Mining on Trace Metal Concentrations in Surface Environments of Michigan's Upper Peninsula. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

Wanty, R. 2015. Trace Metal Stable Isotopes in Mineral-Environment Investigations. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

#### Poster Presentation:

Chiriboga, E. 2015. Sources of Trace Metals. Workshop on Monitoring Trace Metals in the Lake Superior Basin: An Assessment of Techniques and Case Studies. 12-13 November 2015. Odanah, Wisconsin. 70 attendees.

3) Students supported:

Scott Cardiff  
Nelson Institute for Environmental Studies  
550 N Park St.  
70 Science Hall  
Madison, WI 53706-1404

4) Impact:

Organizing and conducting this workshop on recent advances in monitoring and analysis of trace metals was necessary to address three problems related to trace metals in water and sediment in the Upper Great Lakes. (1) Researchers have developed new techniques for studying trace metals, particularly at low levels and for purposes of “fingerprinting” sources of metals, but understanding of those techniques was not widespread. (2) Many research and monitoring projects on trace metals are underway in the region but agencies and academics are not always aware of each other’s projects. (3) Many sources of trace metals contamination and potential contamination exist in the Upper Great Lakes region but understanding of the exact sources, extent, and consequences of that contamination is often incomplete. We sought to address these three problems by bringing together researchers and agencies working on advanced trace metals techniques and working on trace metals projects in the Lake Superior region in a workshop featuring presentations, discussion, and exchange of publications. This has helped not only increase understanding of advanced techniques and research projects in the region, but has also helped create professional connections that should help improve future flow of information on trace metals research techniques and results.

Although we have not specifically evaluated if the workshop influenced a resource management decision or monitoring approach, we expect that the information shared will influence the future methods and monitoring approaches for trace metals by agencies and researchers in the region.

## Wisconsin Water Resources Fellowship: Collaborating with Water Managers

### Basic Information

<b>Title:</b>	Wisconsin Water Resources Fellowship: Collaborating with Water Managers
<b>Project Number:</b>	2015WI334B
<b>Start Date:</b>	3/1/2015
<b>End Date:</b>	2/29/2016
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	2
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Groundwater, Education, Management and Planning
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Jennifer Hauxwell, Jennifer Hauxwell

### Publications

There are no publications.

# Wisconsin Water Resources Fellowship - Annual and Final

**Reporting Period:** 3/1/2015 - 2/29/2016

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## **Project**

WR15R006 - WI Water Resources Fellowship

## **Principle Findings and Significance**

State agencies often are challenged by the ability to attract and recruit professional talent that best suits their needs. Additionally, students with diverse scientific backgrounds oftentimes do not apply to positions in the public service sector. Many factors may account for this disconnect, including perceptions of limited salary flexibility, a sense of an inability to apply scientific knowledge and experience, the complexities of the hierarchical structure of state government, and/or a lack of awareness of career opportunities beyond the traditional academic path. This conflicts directly with employee job satisfaction and long tenures of many Wisconsin state employees who face considerable challenges in managing complex technical problems within a tapestry of diverse societal and political perspectives on water resource management issues. This program is intended to help attract some of the state's best graduate students in water resources management and analysis to gain key experience and perhaps consider state agency careers. This opportunity will allow students to apply and grow both their technical abilities as well as their leadership skills. It also allows state agencies to benefit from knowledge gained by recent graduate students for sound resource management. We envision this investment as a cornerstone of a fellows program that will continue to expand and form a self-sustaining entity on a state level that is similar to the national Sea Grant Knauss Fellows Program.

Over the past year, we developed the concept and details associated with a partnership with the Wisconsin Department of Natural Resources (DNR) – Drinking and Groundwater Bureau. This Bureau coordinates the Wisconsin Groundwater Coordinating Council, an interagency group that is directed by law to assist state agencies in the coordination and exchange of information related to groundwater programs. WRI provided funding for a half-time graduate project assistantship to be stationed at DNR and mentored by DNR technical and policy staff. WRI coordinated the recruitment and administration of the fellowship with weekly reporting from the student and frequent check-ins with the DNR lead mentor.

The primary science-policy goal for this fellowship has been updating the content and aesthetic appeal of the Groundwater Coordinating Council (GCC) Annual Report to the Legislature, which is currently delivered each August as a website hosted by the Wisconsin Department of Natural Resources (DNR). The update for the FY15 report is especially focused on three sections: the landing page “Dashboard”, “Groundwater Quality”, and “Benefits from Projects”. A related goal has been updating the content and aesthetic appeal of the widely distributed DNR publication, “Groundwater: Wisconsin’s Buried Treasure”. This magazine was last revised in 2006, but is seen as a companion resource to the GCC Annual Report since it provides foundational information about groundwater science and groundwater issues in Wisconsin. Work on these goals and other smaller projects has greatly enhanced the fellow’s ability to communicate scientific information to the general public and helped her gain a

better understanding of how scientific concerns relate to policy outcomes.

**Number of Personnel Involved**

- 1 Participating faculty/staff
- 0 Supported post-docs

**Students Supported**

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**Name**

Carolyn Voter

**Affiliation**

University of Wisconsin-Madison

**Degree**

PhD/DSci

**Major/Specialization**

Civil Engineering

**Graduation**

12/2018

**Conference Participation**

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**Title**

American Geophysical Union Fall Meeting

**Location**

San Francisco, CA

**Dates**

12/14/15 – 12/17/15

**Number of supported students attending**

1

**Presentations by Students**

Voter, C. B. and S. P. Loheide, 2015. Changing spatial patterns of evapotranspiration and deep drainage in response to the interactions among impervious surface arrangement, soil characteristics, and weather on a residential parcel. American Geophysical Union, Fall Meeting 2015. abstract #H24F-03.

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**Title**

National Institutes for Water Resources Annual Directors' Meeting

**Location**

Hotel George, Washington, D.C.

### Dates

2/8/16-2/10/16

### Presentations by Staff

Hauxwell, J., and J. Hurley. (9 February 2016). Wisconsin Water Resources Institute – Highlights on Building Bridges Between Research and Society. National Institute for Water Resources (NIWR) Annual Directors' Meeting. Hotel George, Washington, D.C.

### Journal Articles and Other Publications

No journal articles and other publications reported.

### Awards and Achievements

No awards and achievements reported.

### Research Patent or Copyright

No research patents or copyrights reported.

### Completion Summary

The selected student has surpassed expectations in this first critical year of developing a relationship with Wisconsin's natural resource management agency. Based on this initial success, DNR has already committed to partner with WRI 50:50 cost sharing in the next iteration of the fellowship. We have begun the recruitment process for a one-year, full-time postgraduate position to be stationed at DNR's Bureau of Water Quality.

### Key Accomplishments by Fellow:

- Revised content and structure of all 6 topics in the "Groundwater Quality" section to update information, standardize presentation, and improve readability.
- Revised content of all stories in the "Benefits from Projects" section so the portfolio more fully represents GCC priorities and demonstrates how collaboration and work supported by the GCC benefits the people of Wisconsin. The structure of these stories was also changed to standardize presentation and improve readability.
- Revised content of "Groundwater: Wisconsin's Buried Treasure" to include more interviews with people across Wisconsin, more visual content, and a clearer focus on the relationships Wisconsin citizens, agriculture, and the economy have with groundwater.
- Performed additional analysis and written support for an Environmental Impact Statement.

# **USGS Summer Intern Program**

None.

<b>Student Support</b>					
<b>Category</b>	<b>Section 104 Base Grant</b>	<b>Section 104 NCGP Award</b>	<b>NIWR-USGS Internship</b>	<b>Supplemental Awards</b>	<b>Total</b>
<b>Undergraduate</b>	2	0	0	3	5
<b>Masters</b>	1	0	0	1	2
<b>Ph.D.</b>	7	0	0	2	9
<b>Post-Doc.</b>	2	0	0	0	2
<b>Total</b>	12	0	0	6	18

## Notable Awards and Achievements

The University of Wisconsin Water Resources Center increases emphasis on science impacts through Actionable Science initiative

In federal FY15, we increased our emphasis on achieving societal impacts as a result of both federal- and state-funded projects. We launched a series of Web pages on the concept of Actionable Science (<http://www.seagrant.wisc.edu/home/Default.aspx?tabid=509>) for Wisconsin investigators to highlight the opportunities and challenges associated with conducting stakeholder-engaged research, developed descriptive (gold, silver, bronze medal) standards for PIs in outreach, and added a section on outreach in the state-issued call for proposals, reviewer rating criteria, and a mechanism for submitting stakeholder support letters with proposals. Collectively, these actions resulted in notable improvements in the latest round of proposals we received.

To provide student opportunities for Actionable Science, we launched and funded our first ever Water Resources Fellowship in partnership with the Wisconsin Department of Natural Resources (DNR). This half-time student opportunity was a huge success, resulting in significant improvements in the Wisconsin Groundwater Coordinating Council's website and Annual Report to the Legislature, with DNR eager to continue the partnership and providing 50% funding for a full-time postdoctoral fellow in FY16.

Beach nowcasting could make issuing beach health advisories and closing notices significantly more efficient

The University of Wisconsin Aquatic Sciences Center continued to sponsor a postdoctoral fellow so that coastal managers will no longer have to rely on frequent but out-of-date water-quality tests to make public health decisions at the state's 120 Great Lakes beaches. Instead, they'll be testing less frequently and using an approach known as nowcasting to get more timely and accurate information into the hands of beach managers and the public. Dr. Adam Mednick's primary directive is to expand the reach of the nowcast approach which relies on real-time computer modeling of bacteria concentrations to more of Wisconsin's coastal beaches and to help local communities make it a routine practice. Even though the basic nowcasting approach has been around for several years, it represents a seismic shift in beach water-quality monitoring. Typically, beach managers have tracked water-quality conditions and issued warnings based on water samples collected and analyzed for bacteria concentrations in a lab. The problem with that approach is that it typically takes 18-to-24 hours to get the results, which means that those advisory decisions made by a local health or parks department are based on the previous day's conditions. Rather than relying entirely on a daily sampling and testing structure, nowcasting uses computerized statistical models to predict the concentration of E. coli bacteria within a beach's nearshore waters, based on environmental conditions that are readily measurable things like weather conditions, lake currents, wave height and water clarity. The combination of these types of variables can tell us what the likely water quality is, as opposed to having to wait until the next day for lab results. We can, with relative accuracy, predict whether there's a health risk to swimming on a given day. Part of Mednick's role at ASC has been to develop management guidelines for public health departments, to establish a users' group, and to develop online training and help resources so that they can learn to operate nowcasting more efficiently. For more information, please go to:

<http://www.seagrant.wisc.edu/Home/AboutUsSection/PressRoom/Details.aspx?PostID=2034>.

University of Wisconsin Water Resources Center plays a key role in understanding effects of climate change on Wisconsin's Water Resources

Beginning with FY11, the WRI's annual 104(B) allocation was used to expand the scope of the Joint Solicitation to include research on the effects of climate change on Wisconsin's water resources. Priorities for climate change research were established through a partnership with the Wisconsin Initiative on Climate

Change Impacts (WICCI). Established in 2007, WICCI is a university-state partnership created to:(a) assess and anticipate the effects of climate change on specific Wisconsin natural resources, ecosystems, and regions; (b) evaluate potential effects on industry, agriculture, tourism, and other human activities; and (c) develop and recommend adaptation strategies that can be implemented by businesses, farmers, public health officials, municipalities, resource managers and other stakeholders. WRI staff serve in leadership roles within WICCI. Director Jim Hurley serves as co-chair of WICCI's Science Advisory Board, Jennifer Hauxwell (assistant director for research and student engagement) serves on the Water Resources Working Group, and David Hart (assistant director for extension) serves as chair of the Coastal Communities Working Group. Three climate change projects received funding during FY12 and 13 and two additional projects based at UW-Milwaukee and UW-Platteville were funded and completed during FY14 and 15.

University of Wisconsin Water Resources Center responds to concerned Wisconsin citizens over Flint Water crisis

WRI's Information Transfer Program professionals engage in media relations to ensure that water-related messages are shared with varied audiences in varied ways. That builds brand awareness for WRI as a trusted purveyor of knowledge. In this reporting period, one of the information transfer staff members recognized the news value of an unfortunate event—the water crisis in Flint, Mich.—and turned it into a teaching tool. She put forward the WRI director as a source for media outlets and was able to secure two newspaper interviews, a live television interview and a radio interview—all in large Wisconsin media markets.

University of Wisconsin Water Resources Center partners with Wisconsin Sea Grant to reach millions of people

Wisconsin's Water Resources Institute (WRI) and Sea Grant Institute are housed together administratively at the Wisconsin Aquatic Sciences Center (ASC). This structure enables synergies related to water impacts and outreach efforts. Our communications team works hard to extend research results to the people of Wisconsin and beyond. This occurs in a variety of ways, by interacting with investigators and telling the stories of their work through writing, video, and podcasts and then by sharing these products in a variety of ways (website, social media, newspapers, campus news, television, community events, etc.). A list of our 2015 WRI-specific and general ASC communications accomplishments (not including those outreach efforts that are exclusively related to Sea Grant; e.g. Sea Grant website and products) are below. Over the past year, our Center, in some form, reached over 6 million people in telling the stories related to Wisconsin's water resources.

WRI and ASC Communications team summary during state FY 2016 (July 1, 2015-June 30, 2016) (Venue or product—views, downloads or readership:

WRI Website—73,699

ASC Earned media, 170 News Stories—6,085,826

ASC Chronicle, hard copy—2,400

ASC Chronicle, electronic copy—3,269

ASC Chronicle, online views—66,547

ASC Publications Store—17,973

ASC Social media—8,770

Notable Awards and Achievements

Total 6,258,484